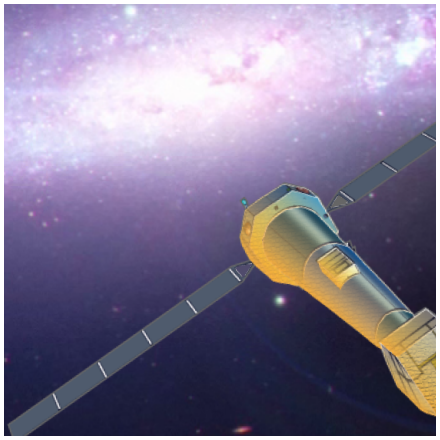
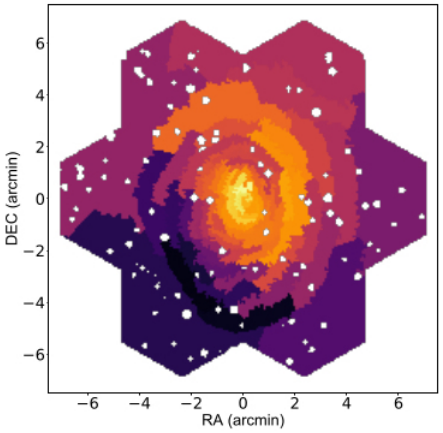
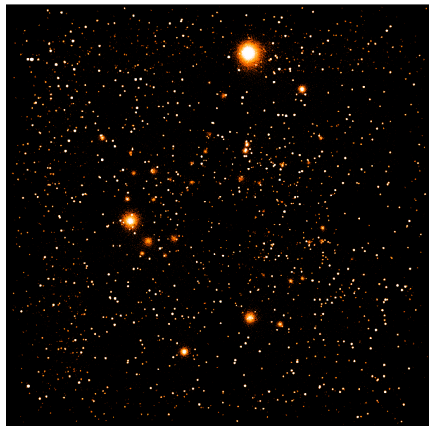
ATHENA

Athena surveys of the Hot and Energetic Universe







Francisco J. Carrera (IFCA)
(on behalf of K. Nandra and the ASST)

Instituto de Física de Cantabria
IFCA (CSIC-UC)
Santander, Spain

X-ray Surveys of the Hot and Energetic Universe,
Harbin (China), January 2019

Contents

- *Athena*: Mission concept & payload
- The *Athena* science theme: Hot and Energetic Universe
- Synergies
- Project development status
- The Athena Mock Observing Plan
- The Athena survey(s)
- Outlook

Thanks to:

- The *Athena* Science Study Team: M. Guainazzi, K. Nandra. D. Barret, J.W. den Herder, A. Decourchelle, A.C. Fabian, H. Matsumoto, L. Piro, R. Smith, R. Willingale
- X. Barcons for the initial presentation
- Athena Working Groups and Instrument Teams

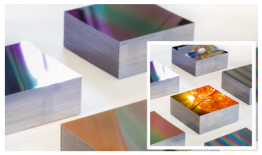
Advanced Telescope for High-Energy Astrophysics

- Second Large (L2) mission of ESA Cosmic Vision
- Science theme: The Hot and Energetic Universe:
  - How does ordinary matter assemble into the large-scale structure we see today?
  - How do black holes grow and shape the Universe?
- Next generation X-ray observatory designed to address science theme
- Broad impact across many areas of astrophysics
- More info at www.the-athena-x-ray-observatory.eu

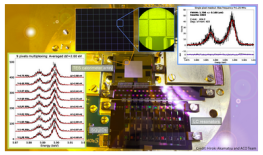
The Athena X-ray Observatory: Community Support Portal

Latest activities & news

"Exploring the Hot and Energetic Universe" conference. 24-27 September, 2018



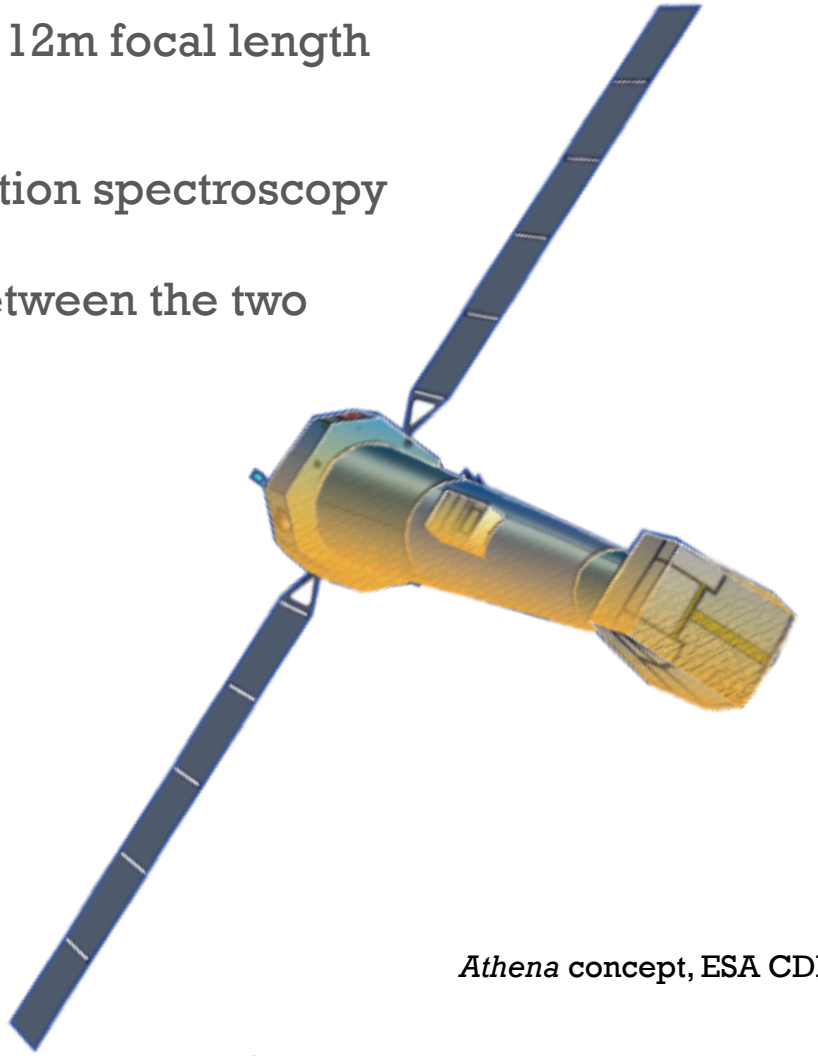
Newsletter #5 (June 2018)



#AthenaNuggets: Reading X-ray detector signals out in MHz frequency space

Athena mission concept

- Single telescope, using Si pore optics. 12m focal length
  - WFI sensitive imaging & timing
  - X-IFU spatially resolved high-resolution spectroscopy
- Movable mirror assembly to switch between the two instruments
- Launch early 2030s, Ariane 6.4
- L2 halo orbit (TBC)
- Lifetime: 4 yr +Possible extensions

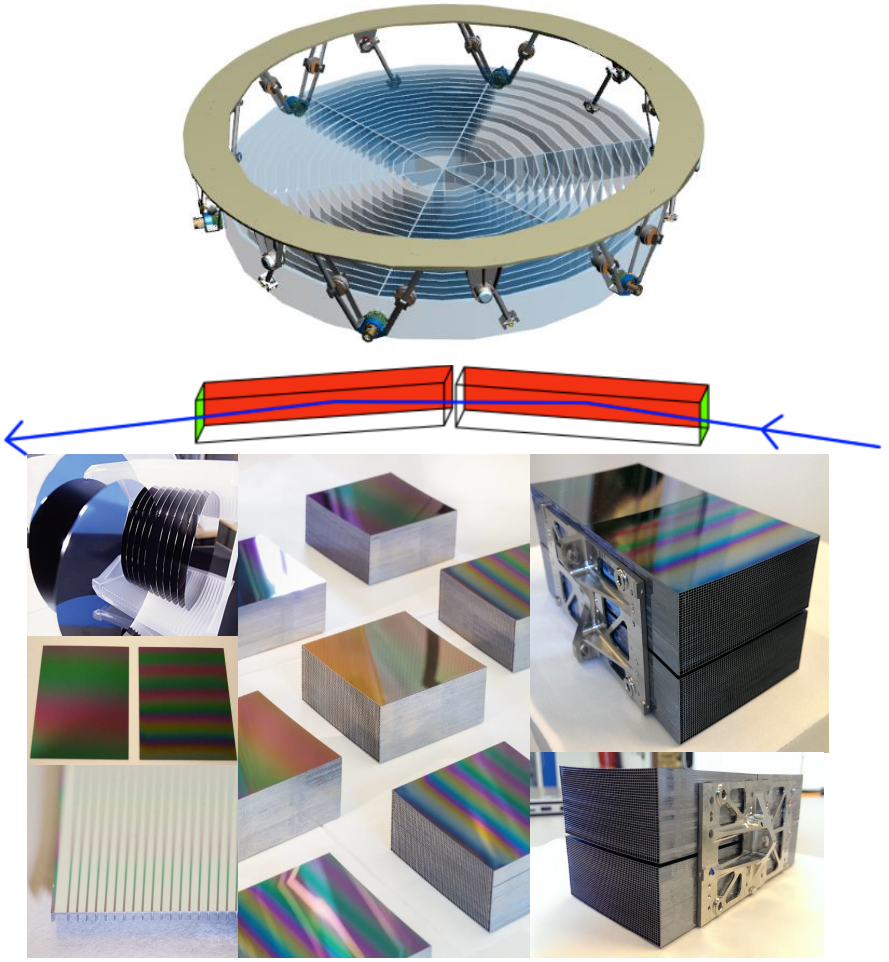


Athena concept, ESA CDF

The Athena X-ray optics

- *Athena* optics development:
  - Light-weight Si-pore optics
  - Grazing incidence optics with Wolter-Schwarzschild type I geometry optimised to provide wide flat field imaging
  - Vigorous development programme on-going

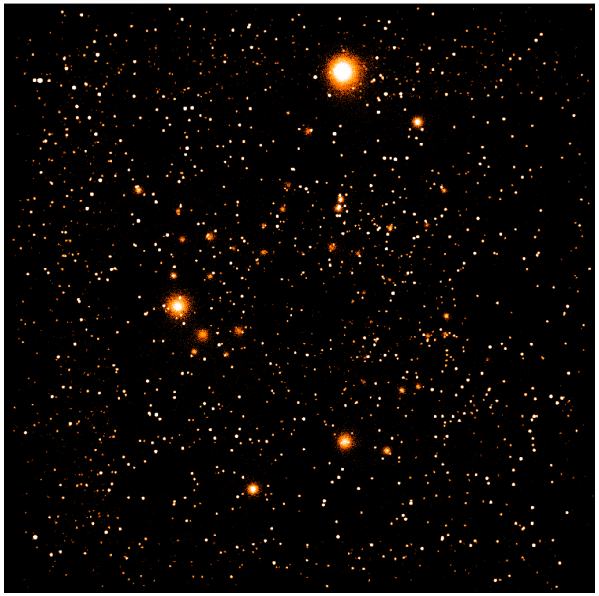
- Expected Performance:
  - 5´´ HEW on-axis
  - Graceful degradation off-axis
    HEW <10´´ @ 30´
  - ≥1.4 m^2 effective area @ 1 keV
    0.25 m^2 effective area @ 6 keV



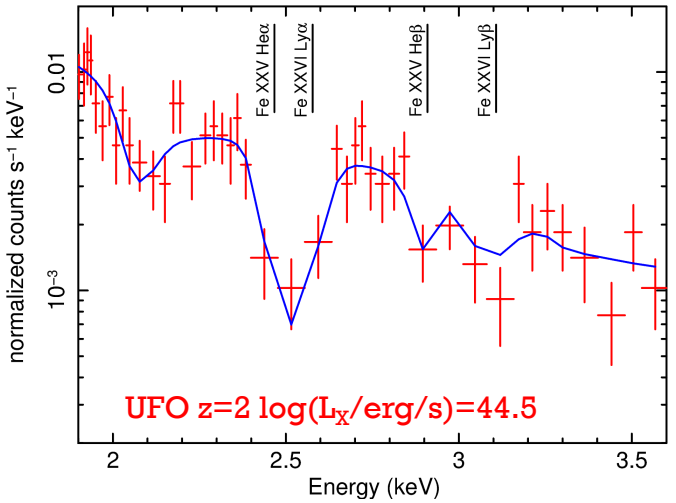
Willingale, Pareschi et al. 2013, arXiV: 1308.6785
Cosine/ESA

Wide Field Imager (WFI)

- Silicon Active Pixel Detector based on DEPFET technology
- Key performances:
  - <80-<170 eV spectral resolution @1-6 keV
  - 2.2´´ pixel size (PSF oversample)
  - Field of view: 40´×40´ square
  - Separate chip for fast readout of brightest sources
  - Readout speed up to ~30 MHz
- Consortium led by MPE, with other European partners (DE, AT, DK, FR, IT, PL, UK, CH, P & GR) and NASA
- Optimized for sensitive wide-field imaging and intermediate resolution spectroscopy, up to very bright sources



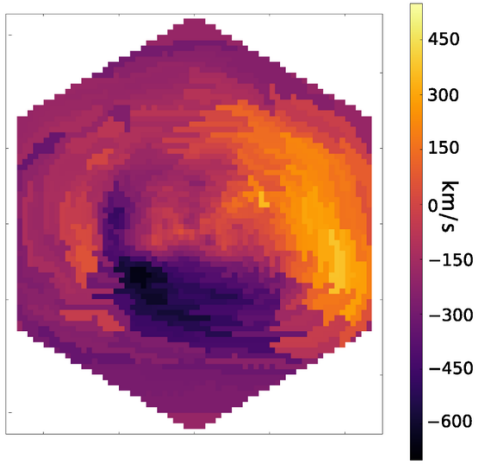
A. Rau/WFI Team



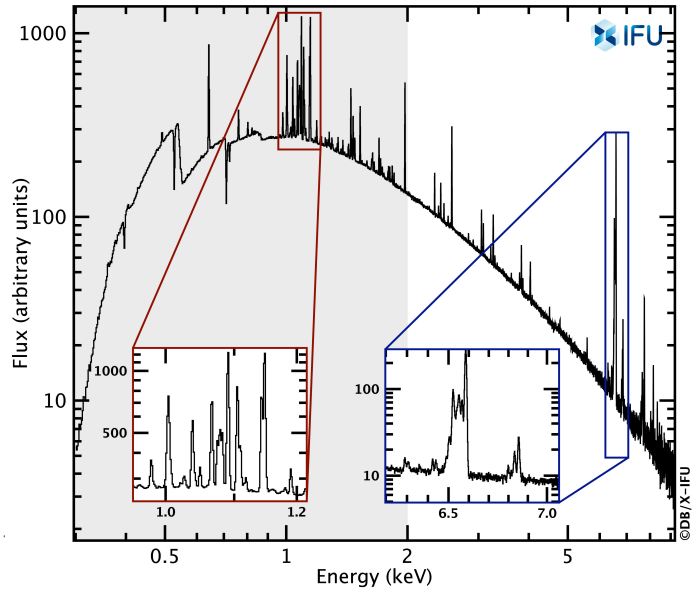
Courtesy: G. Lanzuisi

X-ray Integral Field Unit (X-IFU)

- Cryogenic imaging spectrometer, based on Transition Edge Sensors, operated at 50 mK featuring an active cryogenic background rejection subsystem
- Consortium led by CNES/IRAP-F, with SRON-NL, INAF-IT and other European partners (BE, FI, GE, PL, ES, CH,CZ), NASA and JAXA
- Key performance parameters:
  - 2.5 eV energy resolution <7 keV
  - FoV 5´ diameter
  - Pixel size <5´´



Credit: X-IFU consortium (E. Cuchetti, IRAP)



Credit: X-IFU consortium
Courtesy: C. Pinto, A.C. Fabian

The Hot and Energetic Universe

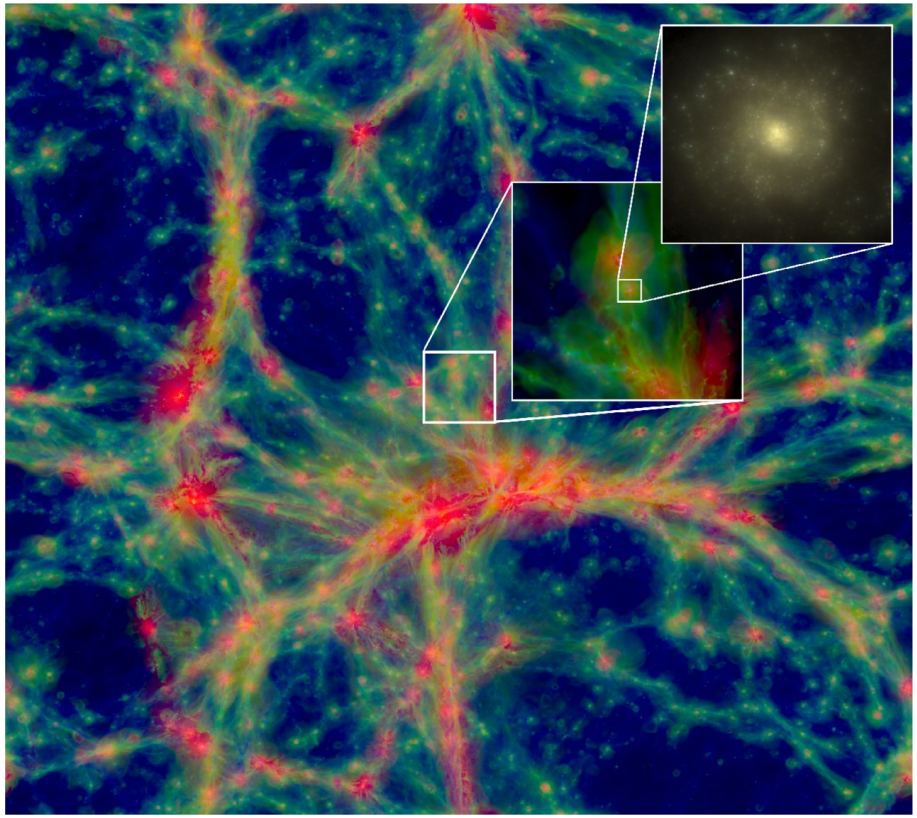
- The Hot Universe: How does ordinary matter assemble into the large-scale structures that we see today?
  - >50% of the baryons today are in a hot (>10^6 K) phase
  - Now there are as many hot (> 10^7 K) baryons in clusters as in stars over the entire Universe
- The Energetic Universe: How do black holes grow and influence the Universe?
  - Building a SMBH releases 30× the binding energy of a galaxy
  - 15% of the energy output in the Universe is in X-rays

Nandra, Barret, Barcons et al. arXiv:1306.2307

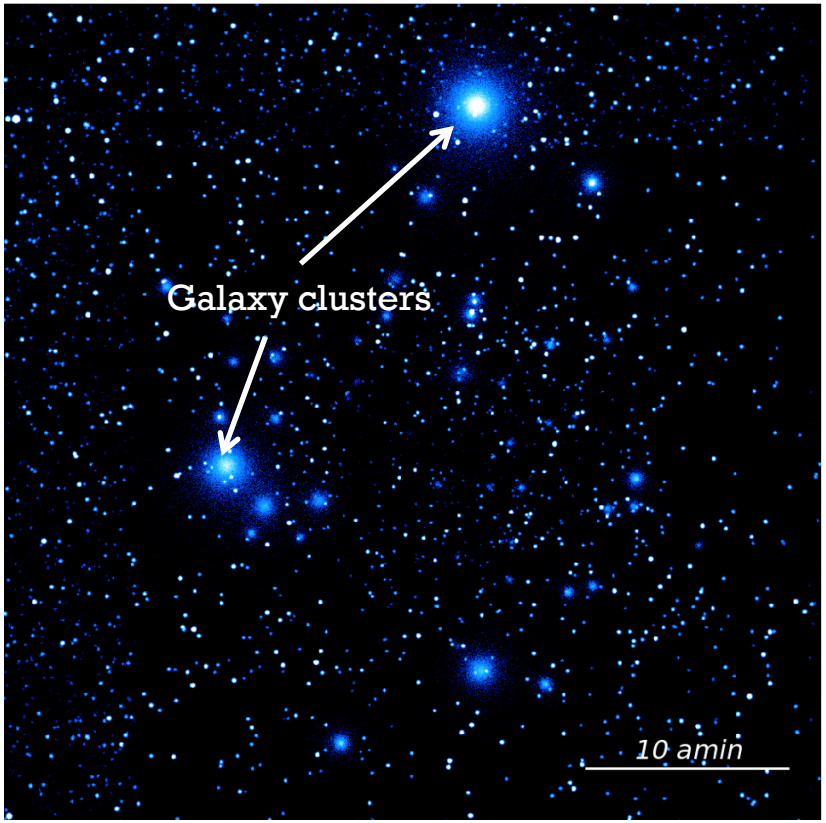
The Hot Universe – baryonic assembly

EAGLE cosmological simulation

$T<10^{4.5}$ K $10^{4.5}\leq T\leq 10^{5.5}$ K $T>10^{5.5}$ K



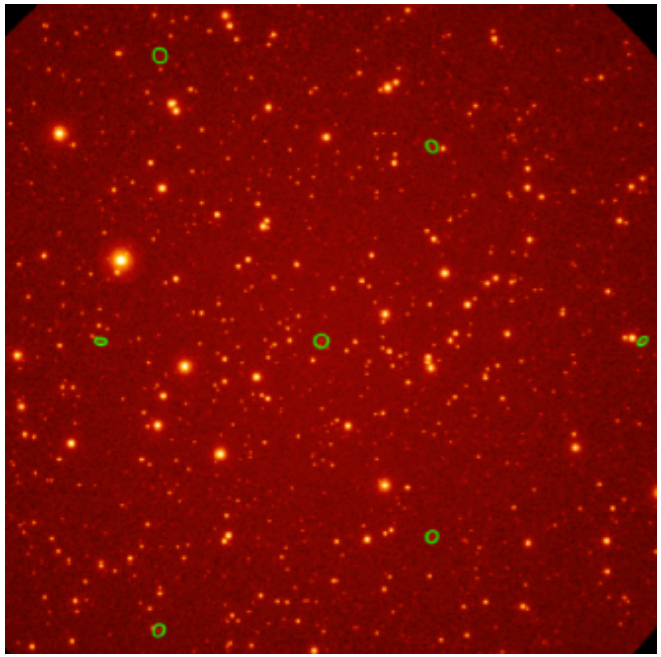
Schaye et al. 2015



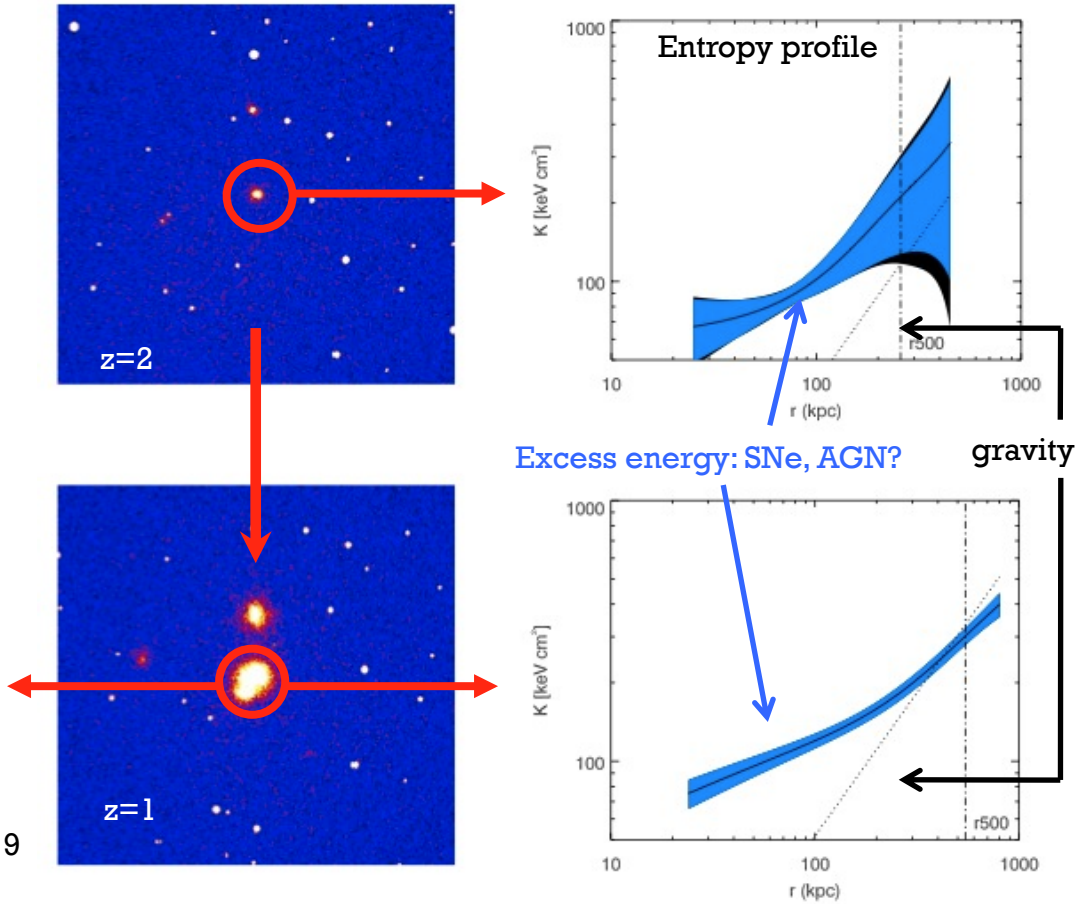
Athena/WFI 1Ms simulation
MPE & WFI team

Evolution of hot cluster gas

Search for early groups of galaxies at z>2



Energy deposition history

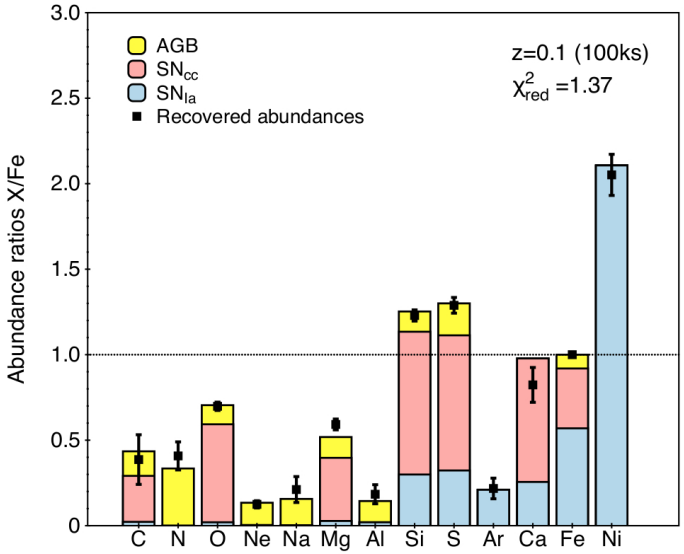


Ettori, Pratt et al. 2013, arXiv1306.2322
Pointecouteau, Reiprich et al. 2013, arXiv: 1306.2319

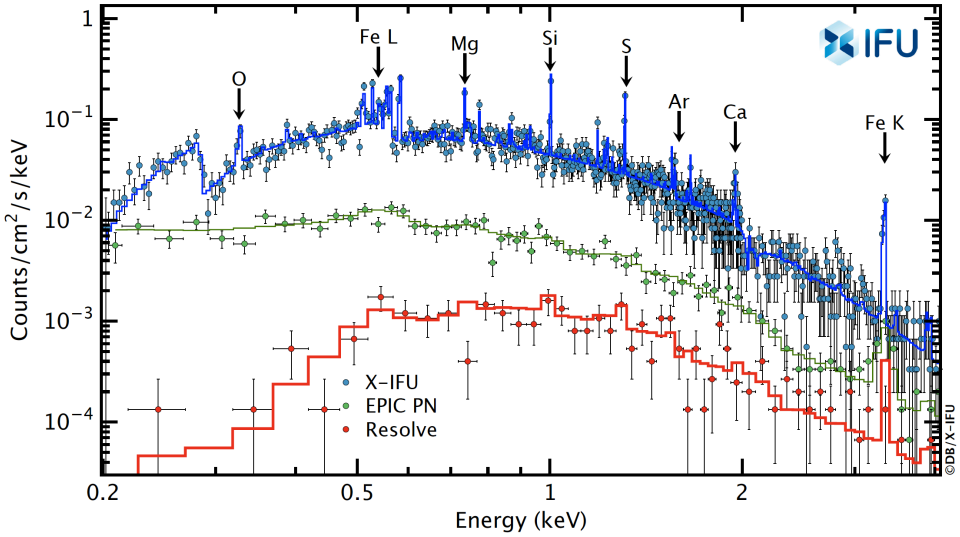
Chemical evolution

- Clusters of galaxies are closed boxes, all gas is virialised in the DM potential well
- Cosmic chemical evolution traced by cluster gas
- Constraints on origin of elements and IMF

Cucchetti et al. 2018



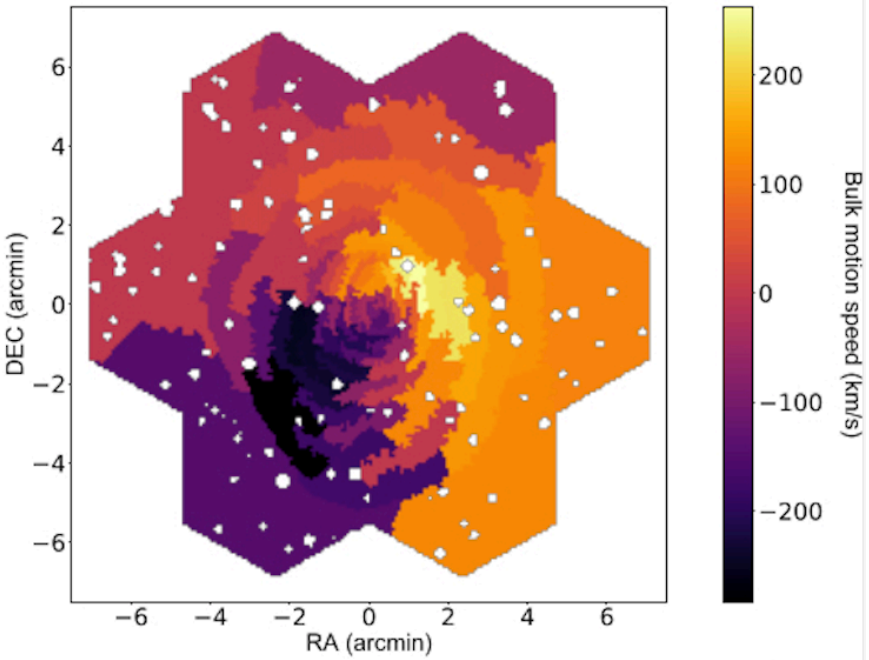
Galaxy group @z=1 150ks
Athena/X-IFU



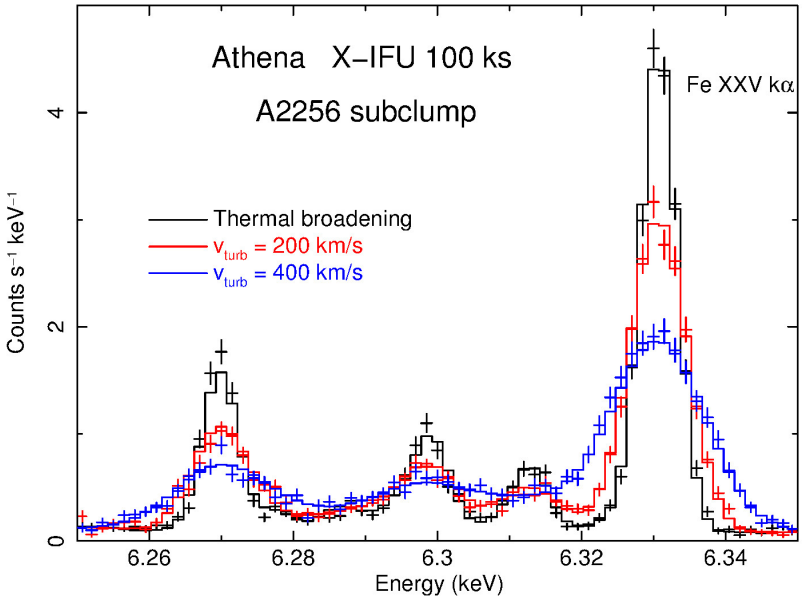
Credit: X-IFU consortium

Cluster bulk motions & turbulence

Athena will measure gas bulk motions and turbulence down to 20 km/s



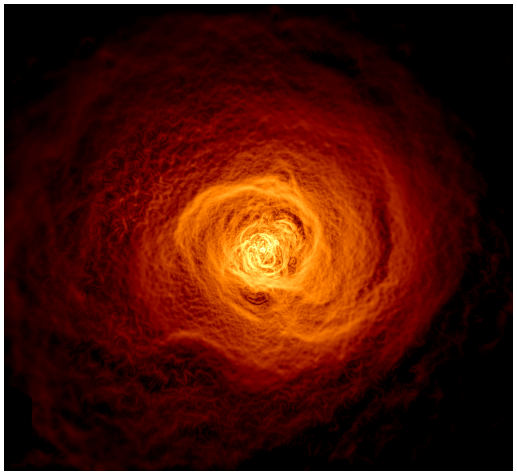
Bulk velocity map: Cucchetti et al. 2018



Ettori, Pratt et al. 2013 arXiv1306.2322
Pointecouteau, Reiprich et al. 2013, arXiv: 1306.2319

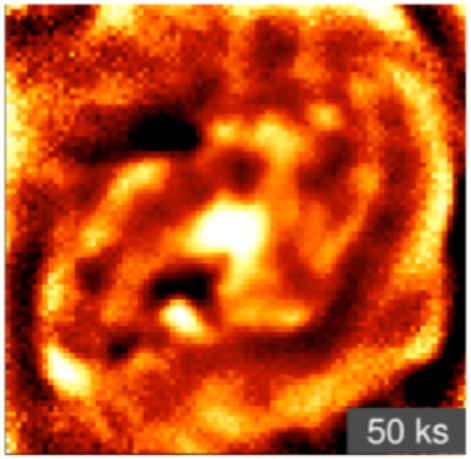
AGN feedback on cluster scales

- Dissipation of AGN energy into ICM
  - Energy stored in hot gas around bubbles via bulk motions and turbulence
  - History of radio cluster feedback via ripples
  - AGN jet fuelling vs. cooling through temperature distribution
  - Shock speeds of expanding radio lobes

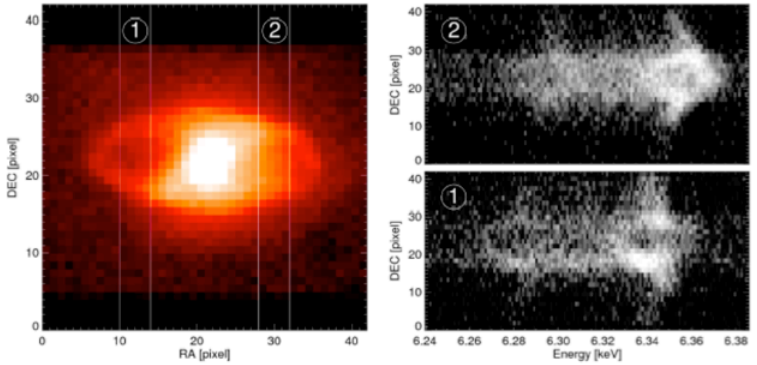


Perseus cluster. Courtesy: A.C. Fabian

Athena/WFI unsharp mask observation of a cluster core at z=0.05



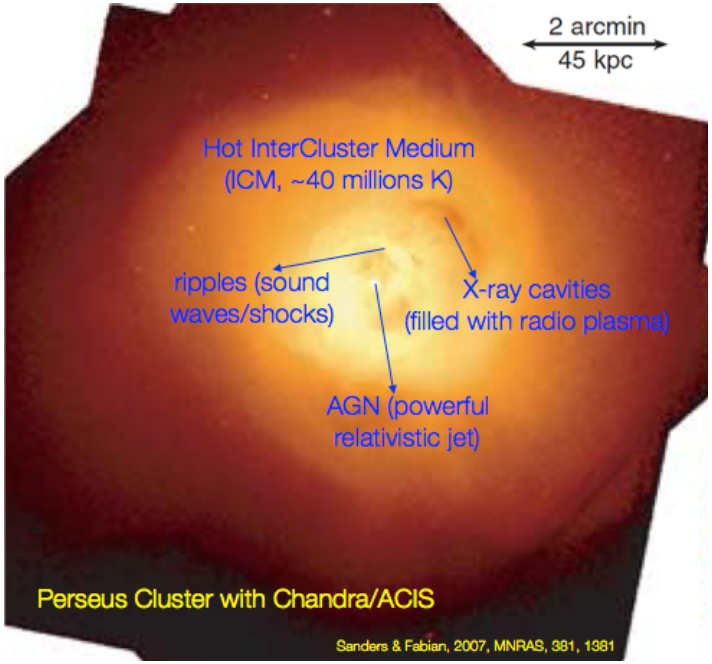
Cygnus A: X-ray image and chosen virtual spectral slits (left) and *Athena*/X-IFU spatially resolved simulated spectra of the 6.7 keV Fe XXV Kα line (right)



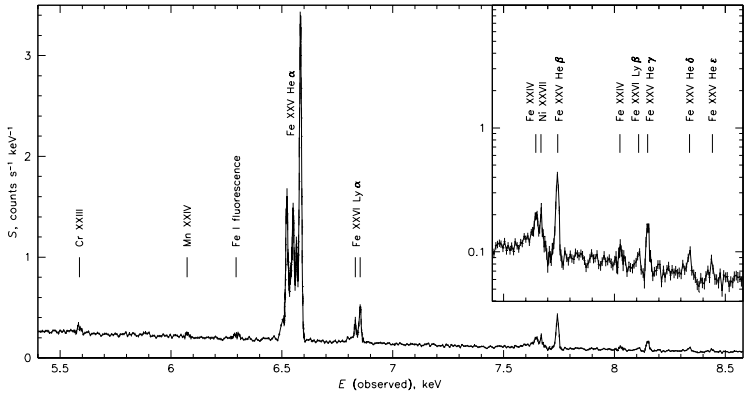
Croston, Sanders et al. 2013 arXiv1306.2323. Simulations by S. Heinz

Hi-res spectroscopy in action: Hitomi (Feb-Mar 2016)

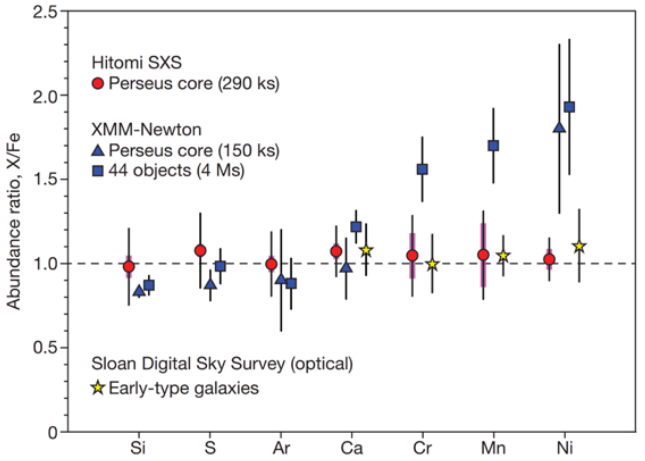
The *Hitomi*/SXS (non-dispersive micro-calorimeter) is the first X-ray instrument resolving emission lines in extended sources and measuring their Doppler broadening and shifts



The quiescent intracluster medium in the core of the Perseus cluster. Hitomi Collaboration, Nature, 2016

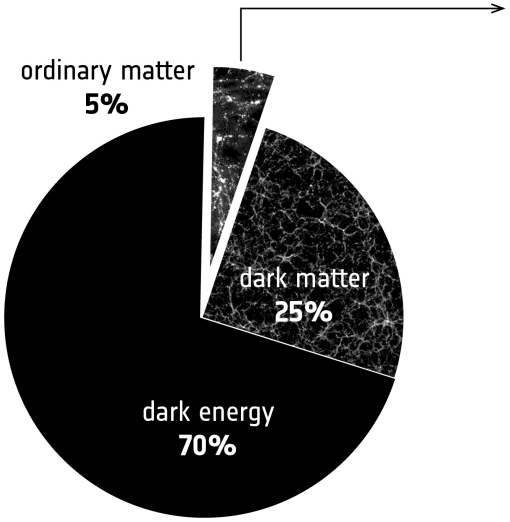


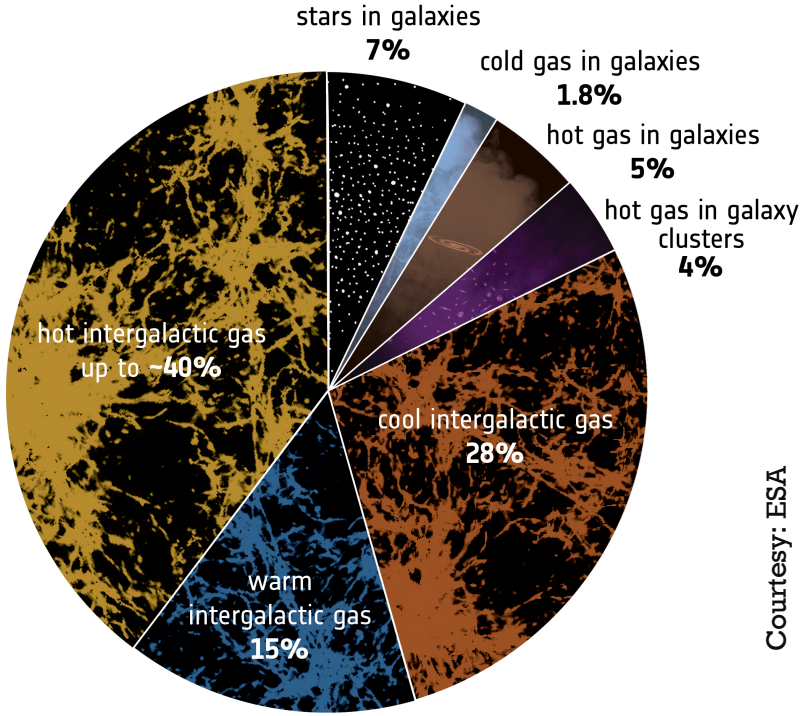
Solar abundance ratios of the iron-peak in the Perseus cluster. Hitomi Collaboration, Nature, 2017



Missing baryons: the WHIM

- Cosmological hydro simulations show ~50% of baryons at low redshift at **T~10^5-10^7** K in the IGM
  - Unvirialised and filamentary distribution
- How can they be detected?
  - In absorption:
    - Against a **bright background sources (AGN or GRB afterglow)**
  - In emission:
    - Tenuous and extended
    - Key to understand CGM and feedback



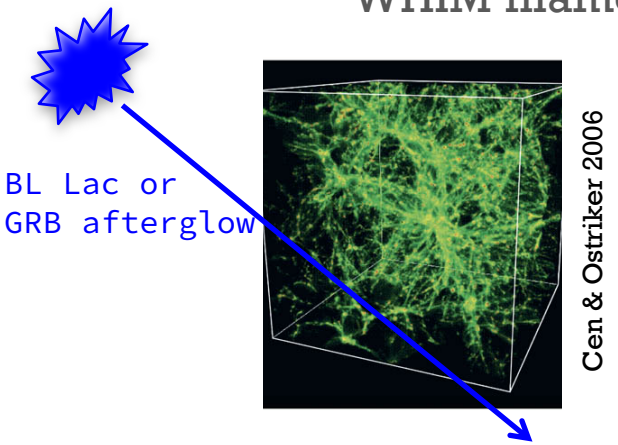


Courtesy: ESA

CSIC

Detecting the WHIM baryons in absorption

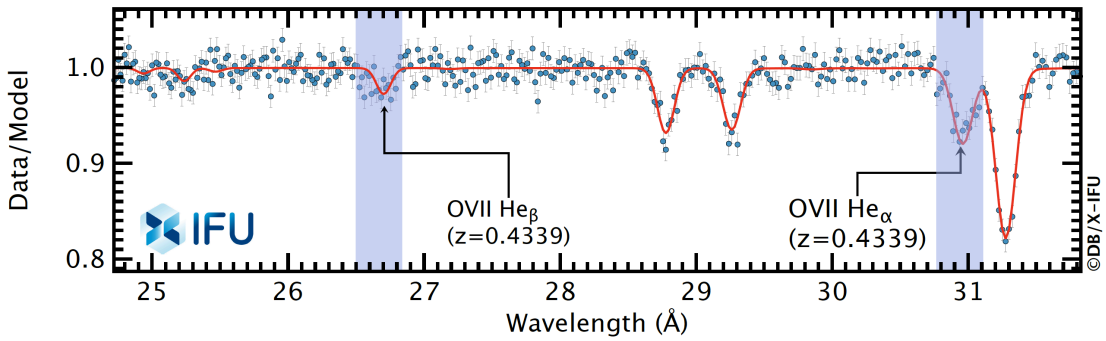
WHIM filaments against brightest GRB afterglows



XMM-Newton finds missing baryons observing a blazar at z > 0.4 !

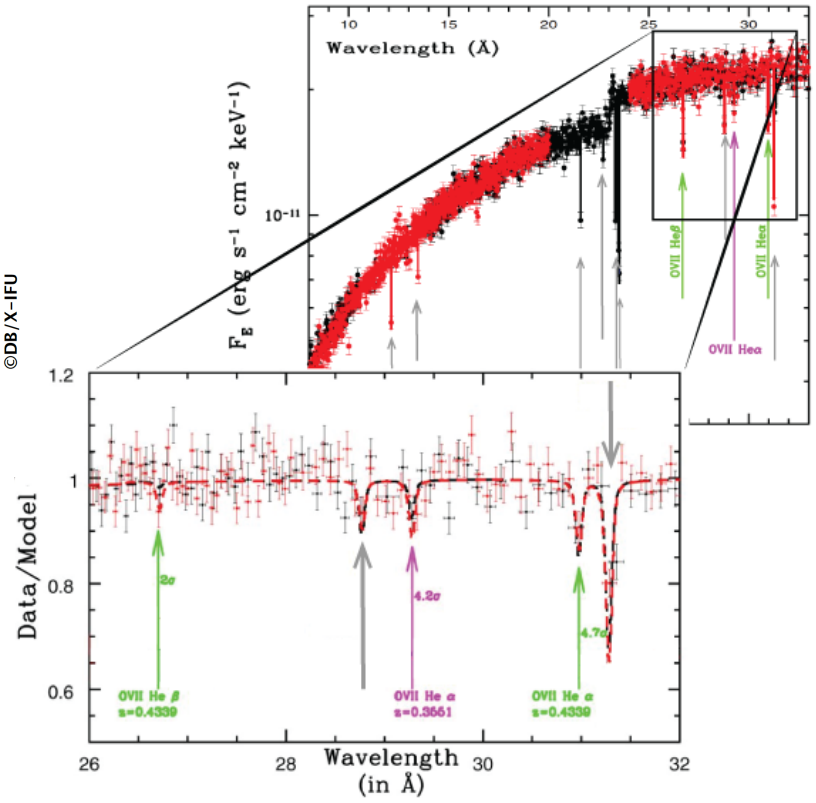
Nicastro et al., Nature, 2018

Athena/X-IFU, same blazar 150ks



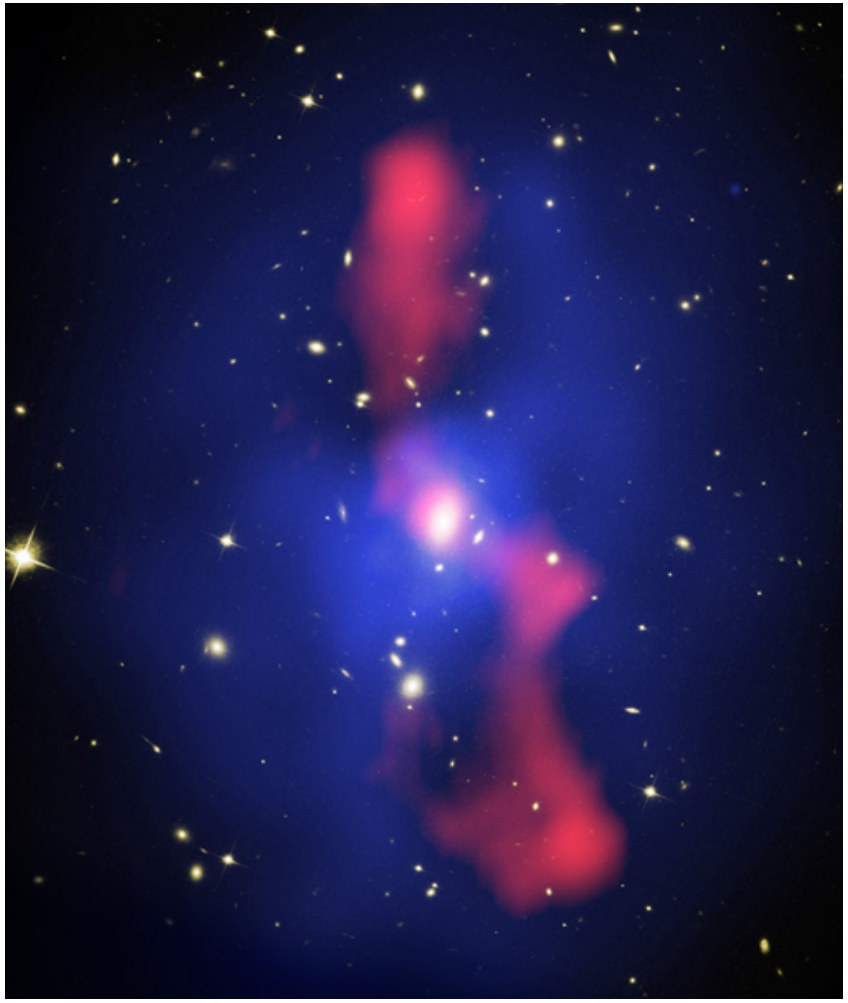
Courtesy: F. Nicastro, X-IFU consortium

XMM-Newton/RGS, Blazar z>0.4, 1.85Ms

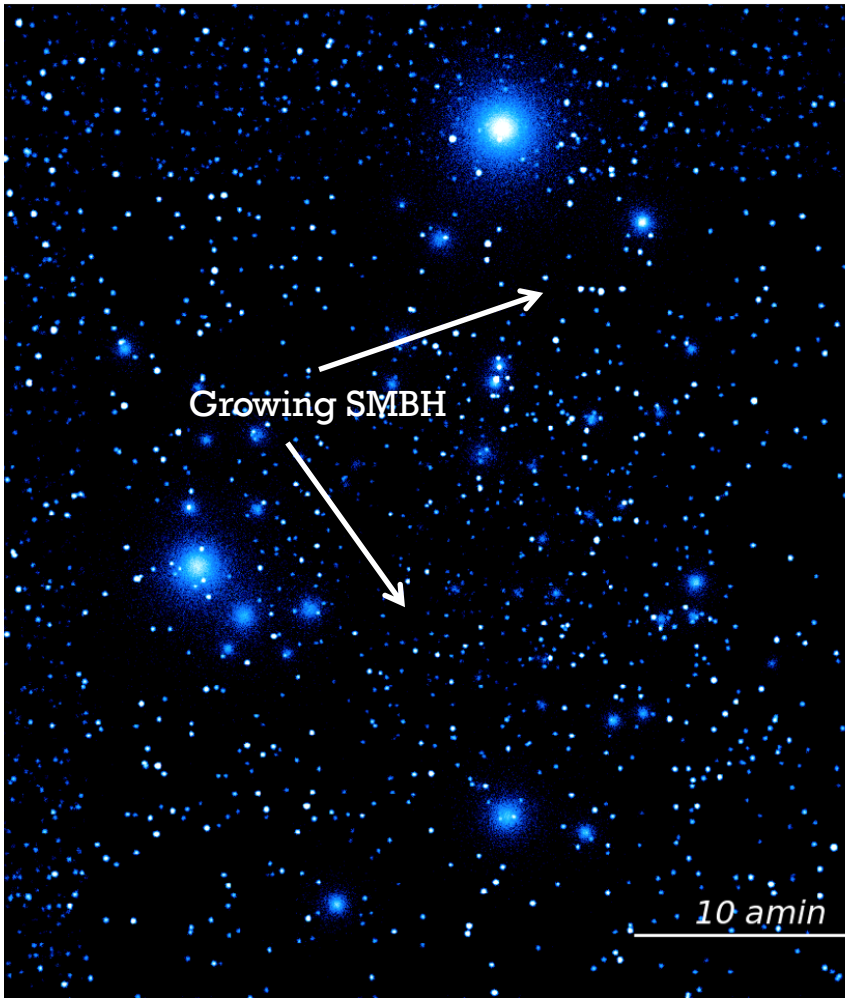


Instituto de Física de Cantab

The Energetic Universe – Black Holes



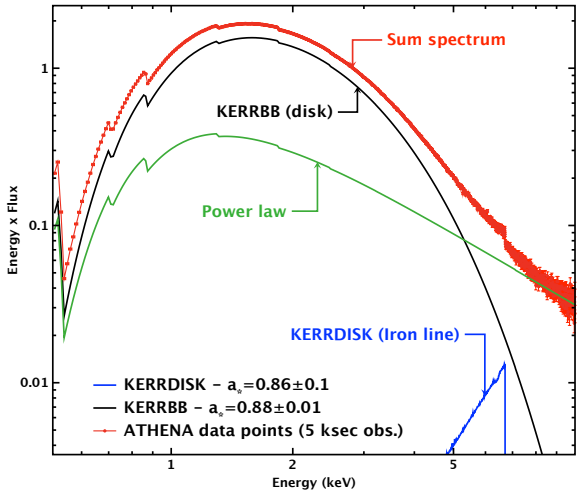
MS0735.6+7421 McNamara et al. 2005

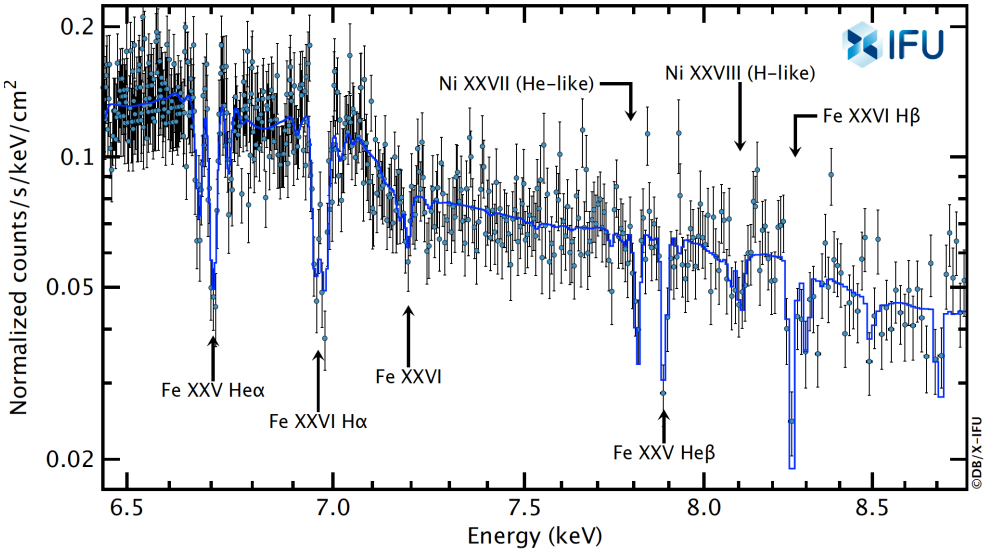


Athena/WFI 1Ms simulation
MPE & WFI team

Stellar black holes

- Measure BH spins
  - Constraints on SN origin
  - Relation to jets
- Accretion geometry
  - Disc truncation from lag spectra
  - Winds as diagnostics of the accretion flow

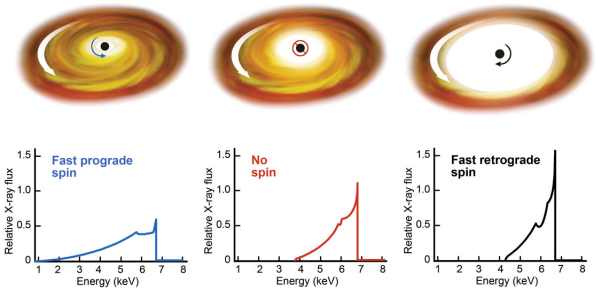




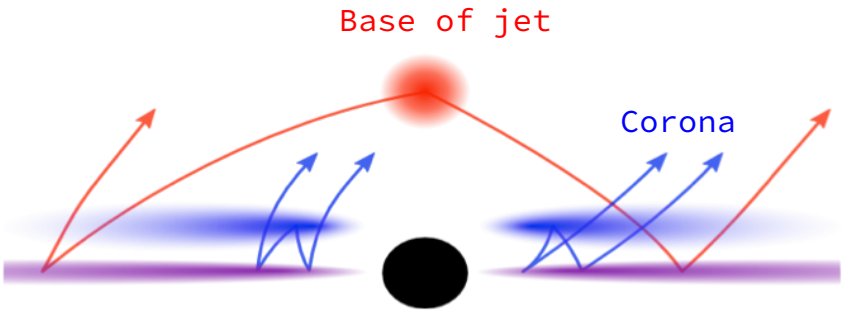
Courtesy J.M. Miller and the X-IFU consortium

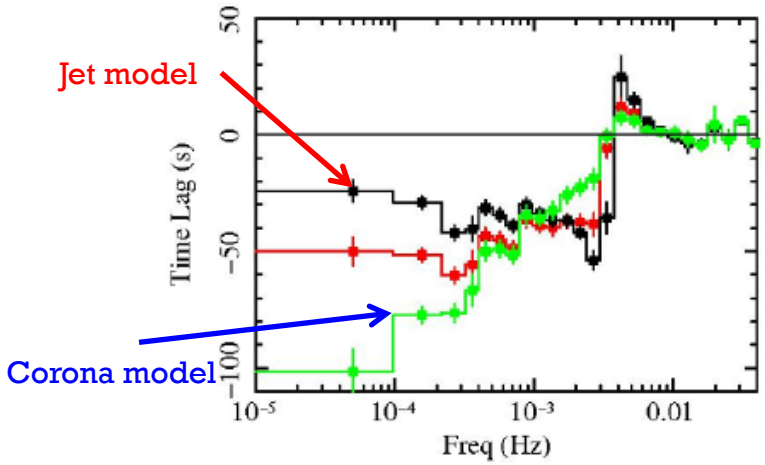
Supermassive Black Hole physics

- Measure SMBH spins through Fe line spectroscopy



- Accretion geometry and jet/disk relation through reverberation mapping

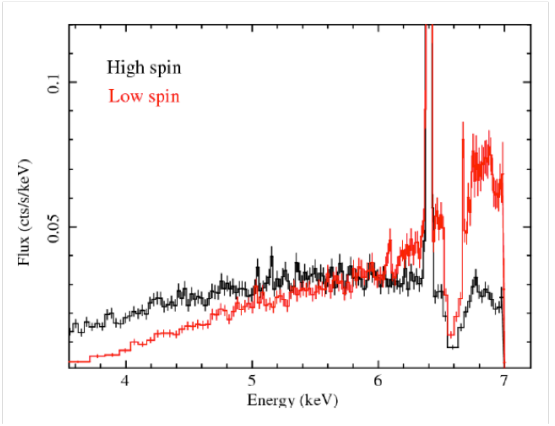


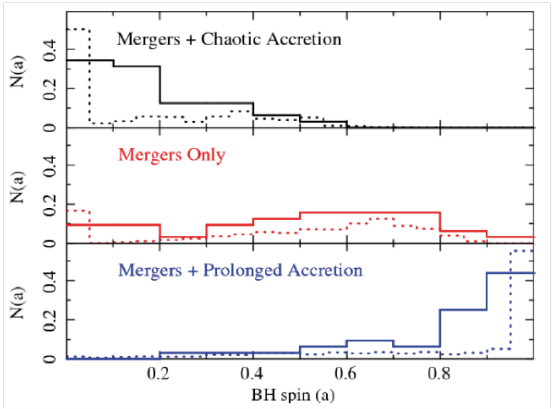


Dovciak, Matt et al. 2013, arxiv:1306.2331

SMBH growth: accretion vs mergers

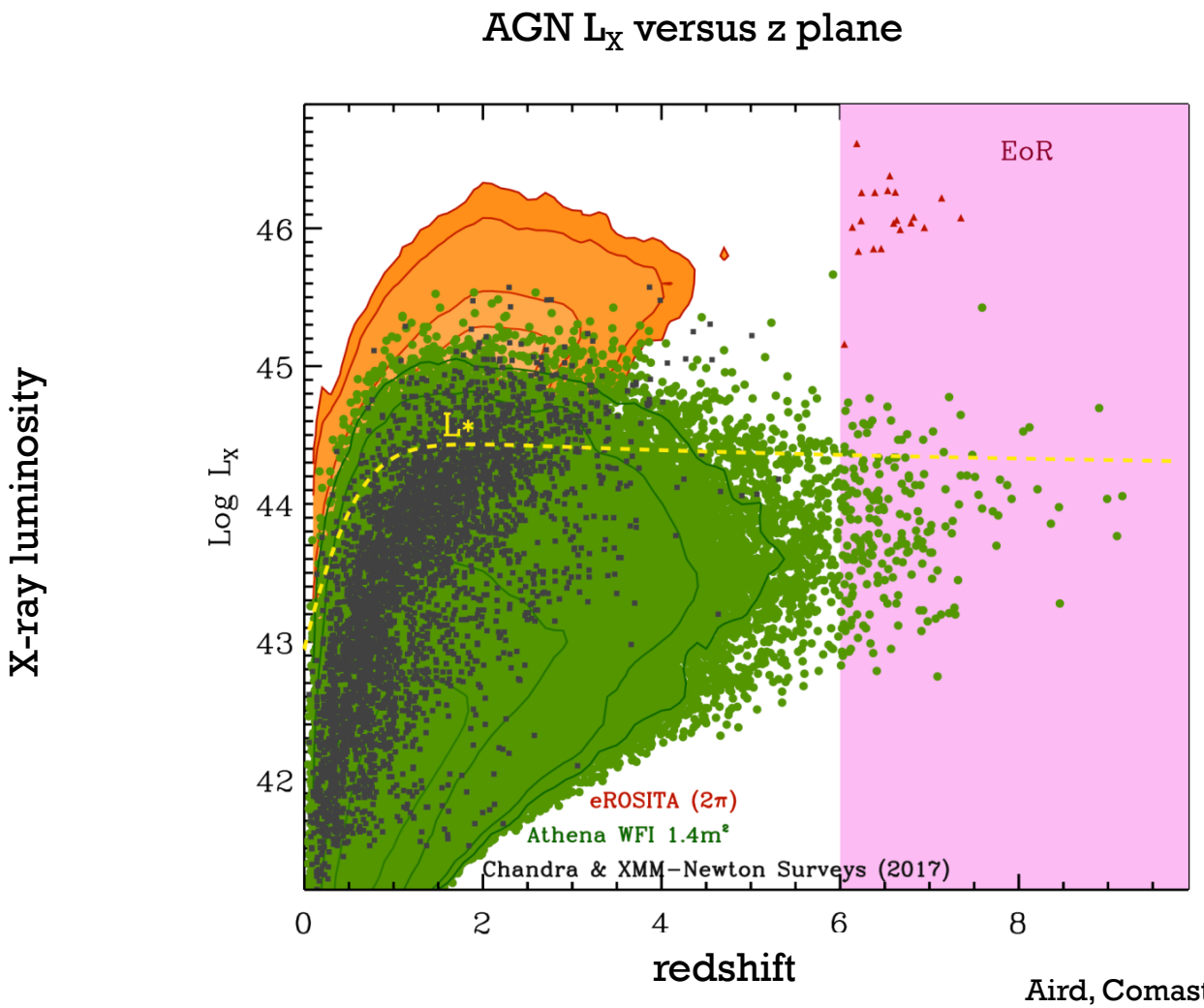
- SMBH spin distribution is highly sensitive to SMBH growth history
  - Accretion spins up SMBH
  - Mergers & chaotic accretion spin down SMBH
- A SMBH spin survey with *Athena* will reveal dominant SMBH growth mode
  - Partly doable with XMM-*Newton*, but for removal narrow features





Dovciak, Matt et al. 2013: arXiv 1306.2331
simulations by G. Miniutti

The history of SMBH growth



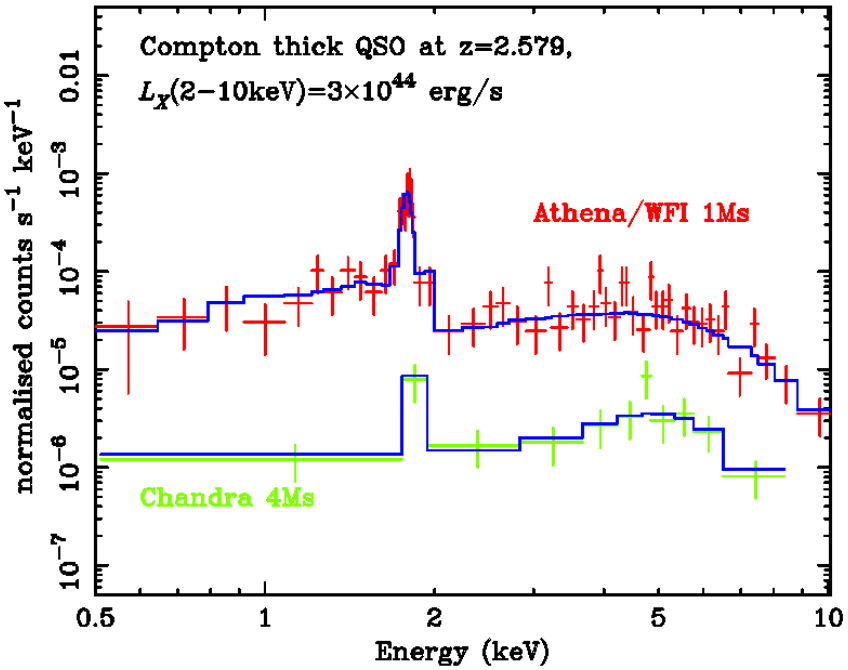
Only most luminous /massive QSOs expected in opt/IR surveys

X-rays needed to signpost typical and obscured AGN

Aird, Comastri et al. 2013 arXiv1306.232
Updated by Andrea Merloni (MPE) (2017)

Obscured AGN census @ z~1-3

- What is the relation between obscured growth of SMBH through cosmic history and how does it relate to galaxy formation?
  - Most SMBH growth expected in heavily obscured (including Compton-Thick) environment
  - Best X-ray signature of typical Compton-thick AGN is the Fe emission line, EW ~0.5-1 keV
  - *Athena*/WFI observations can uncover Compton-Thick average AGN at z~3
  - MIR observations can also uncover heavily obscured AGN, but **only** when the AGN is very powerful

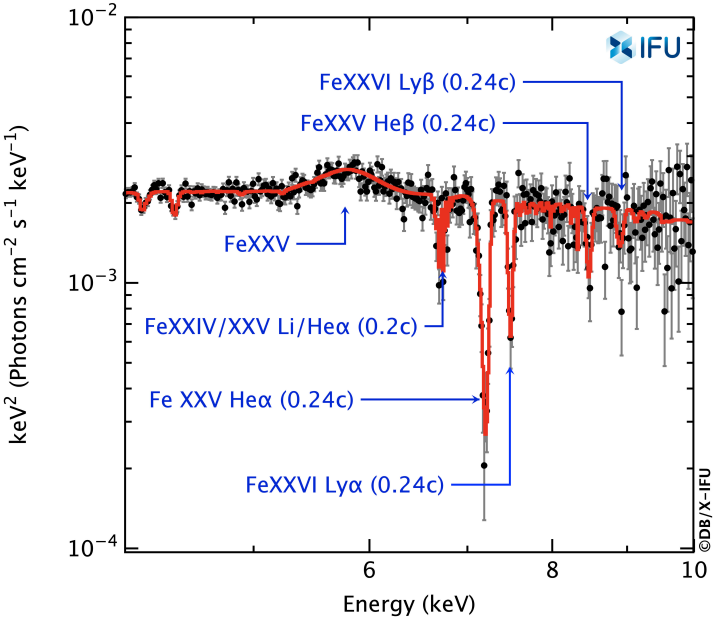


Carrera et al. 2018, Athena conference

AGN winds and outflows

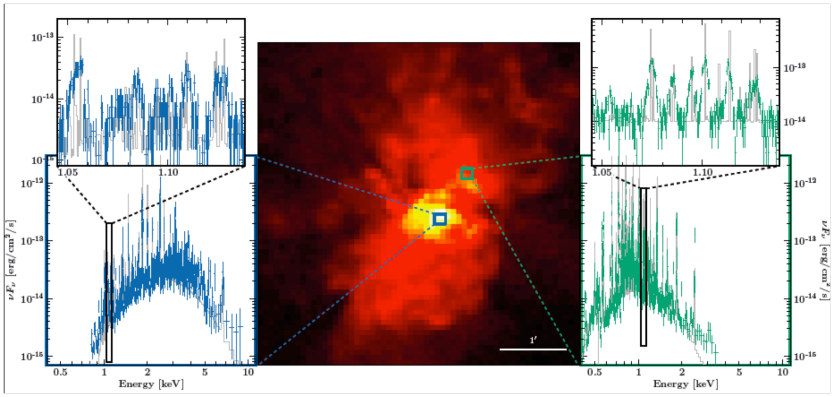
Mechanical feedback effective if $L_{mech} > 1\% L_{bol}$

Mechanical energy released in ultra-fast outflows αv^3



PDS456 100ks X-IFU (X-IFU Consortium)

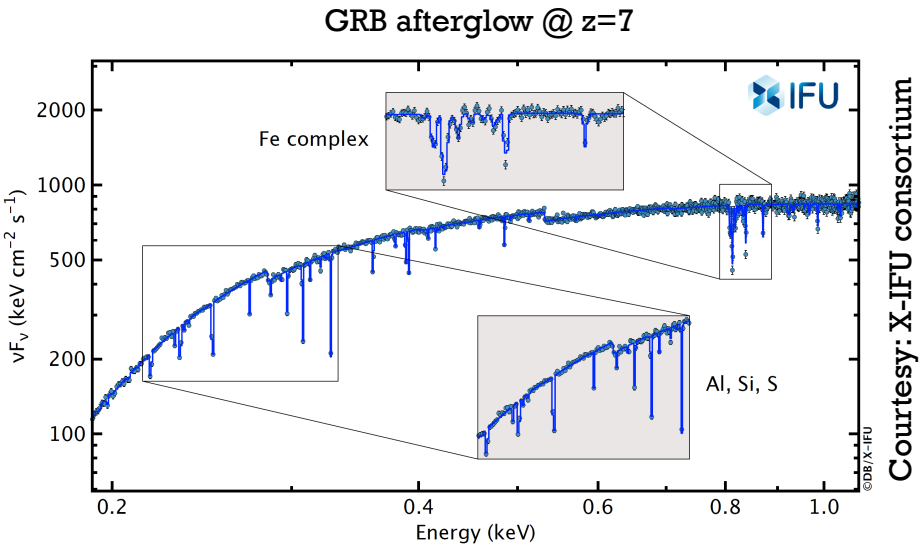
Gas, metals and mechanical energy ejected into the circum-galactic medium by AGN and Starbursts

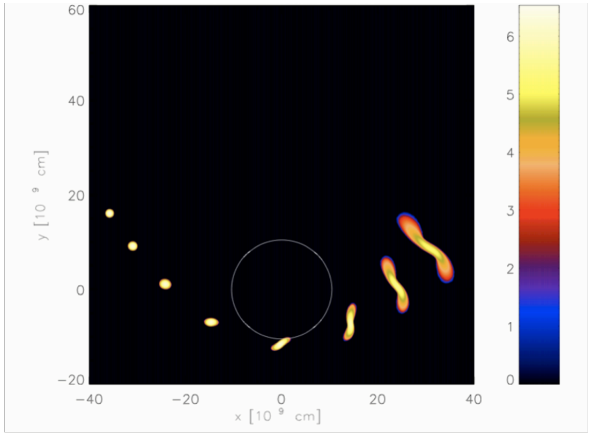


A. Ptak and the *Athena* simulation team (in progress)

Luminous extragalactic transients

- *Athena* will offer fast Target of Opportunity response, whereby a triggered observation could start in ≤ 4 hours
  - 40% of GRB afterglows anywhere on the sky can be followed-up by X-IFU with at least 50 ks t_{exp}
- High-z GRB afterglows will reveal the ISM composition at z>7-10
- Tidal Disruption Events (TDEs) result from the destruction of a star by a SMBH. *Athena* will
  - Unveil SMBH through this
  - Reveal the composition of the outflowing material
  - Test for the presence of binary SMBH





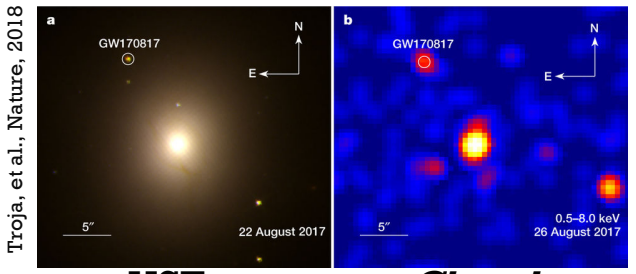
Jonker, O'Brien et al. 2013: arXiv 1306.2336
Rosswog, Ramirez-Ruiz & Rix (2009)
Courtesy: P.T. O'Brien and P. Jonker

Chasing the transient Universe with Athena

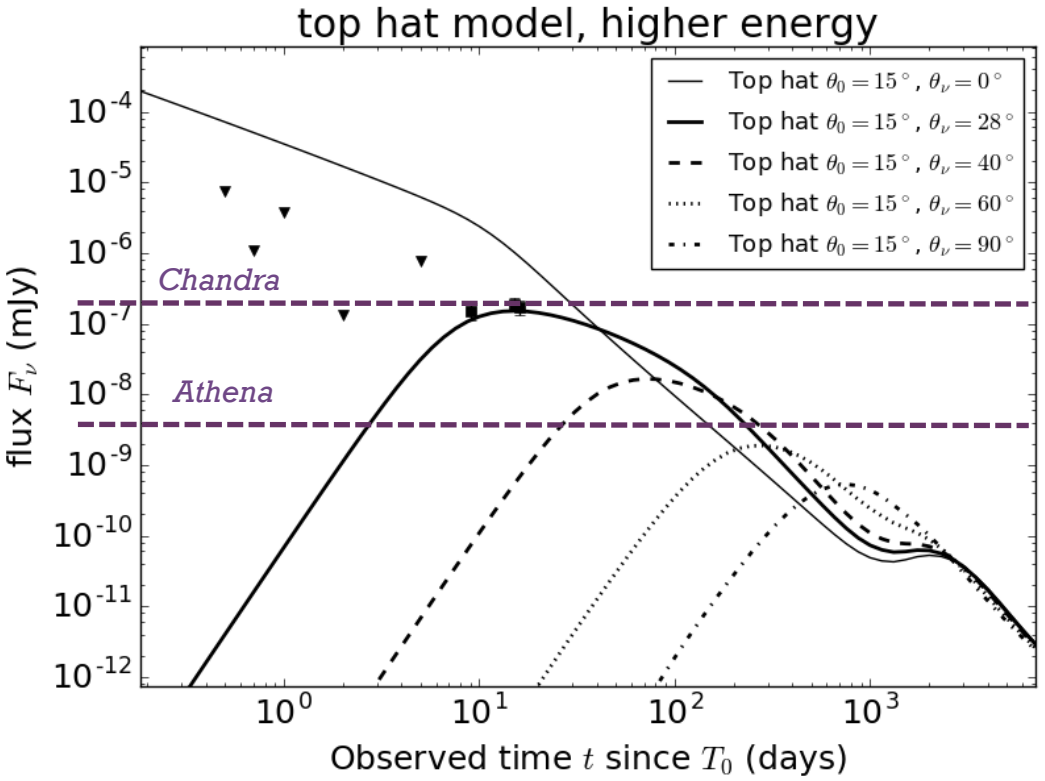
- X-rays probe:
  - Jet: GRB afterglow (from radio to X-rays)
  - Isotropic features:
    - Off-axis (orphan) afterglows
    - Cocoon
- Beaming angle ~$1/\Gamma$

Athena needed for any line-of-sight ≥40° (~70% of potential GRBs)

GW170817 counterpart



HST *Chandra*

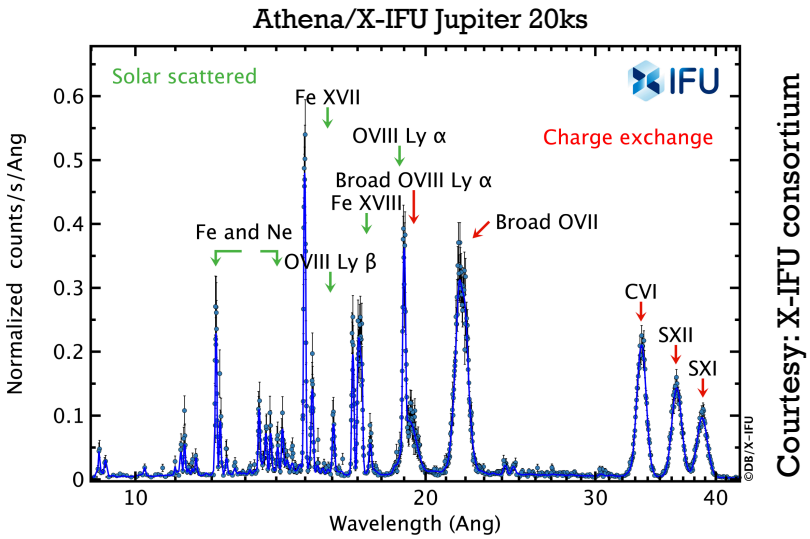


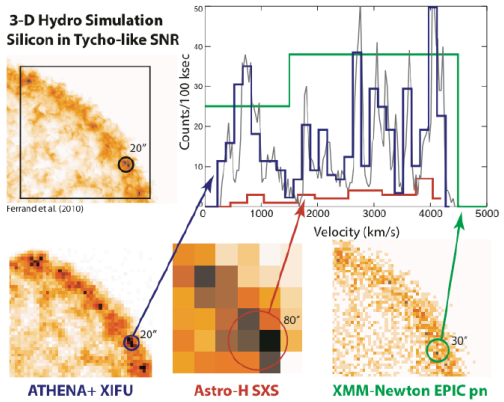
Courtesy L.Piro (IAPS/INAF)

Observatory and discovery science

- Planets and solar system bodies
- Exoplanets: magnetic interplay
- Star formation, brown dwarfs
- Massive stars: mass loss
- Supernovae: explosion mechanisms
- Supernova remnants: shock physics
- Stellar endpoints (NS)
- Interstellar medium
- Dark matter candidates
- …

~ 2/3 (TBC) of the *Athena* nominal operational life will be allocated to the international astronomical community through a competitive peer review process

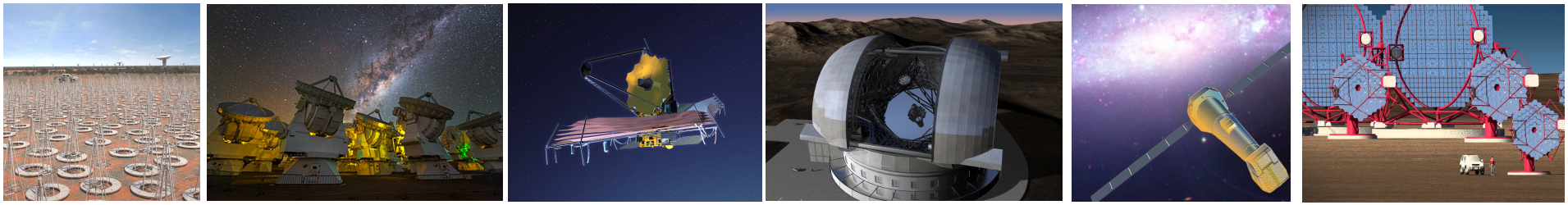


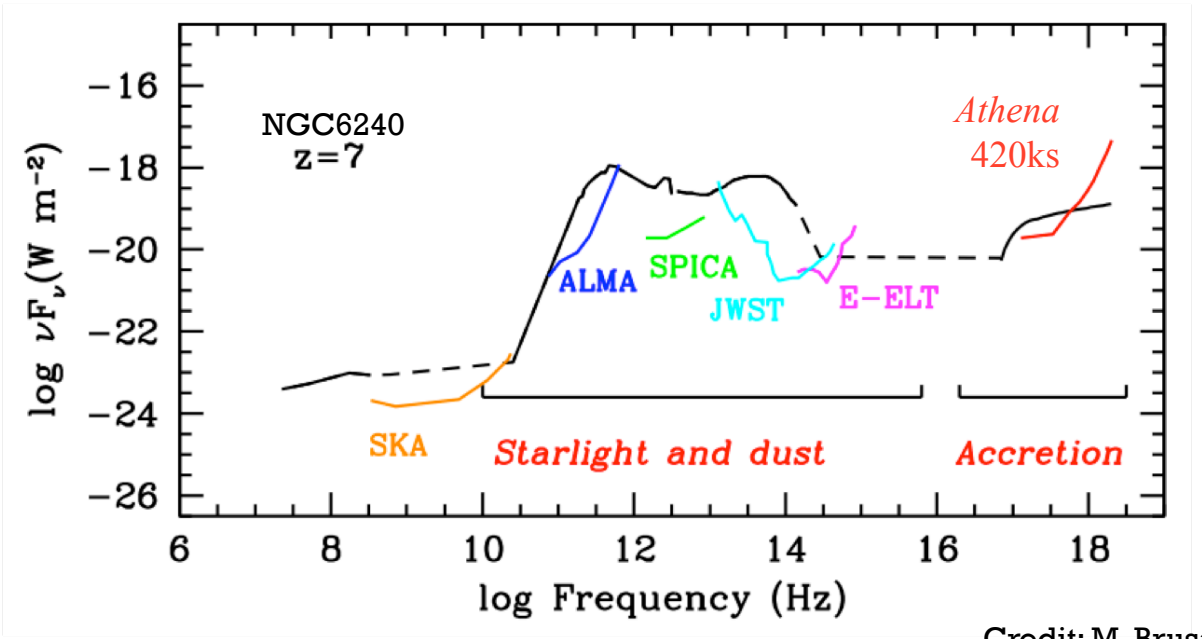


Decourchelle, Costantini et al. 2013: arXiv 1306.2335
Motch, Wilms et al. 2013: arXiv 1306.2334

Athena in the framework of the late 2020s

SKA | ALMA | *JWST* | ELT | *Athena* | CTA

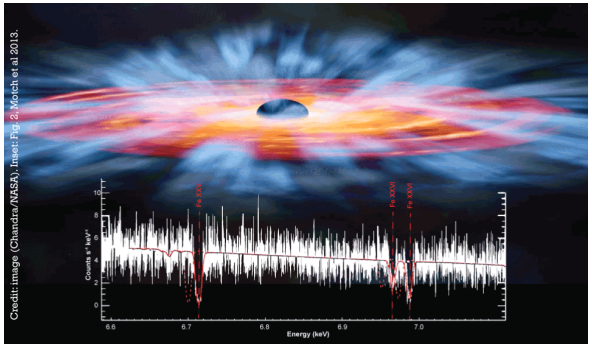




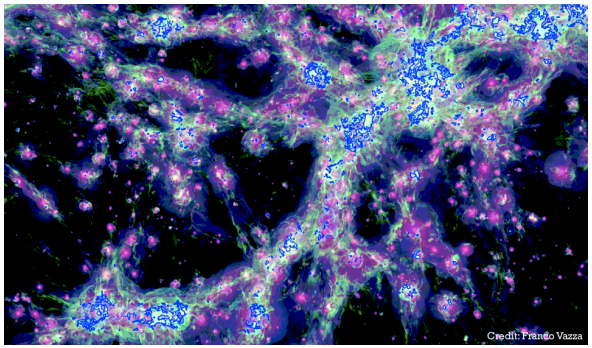
Credit: M. Brusa (Nandra et al. 2013)

Athena Synergies with other facilities I

- ESO-*Athena*
  - Led by: P. Padovani (chair), E. Hatziminaglou, M. Díaz-Trigo, S. Viti, S. Ettori, M. Salvato, F. Combes, P. Jonker
  - arXiv:1705.06064
  - Early groups & clusters, IM physics, missing baryons, SMBH history, AGN feedback, outflows, transient science, star formation & stars



- SKA-*Athena*
  - Led by: R. Cassano (chair), R. Fender, C. Ferrari, A. Merloni
  - arXiv:1807.09080
  - AGN, clusters & transients



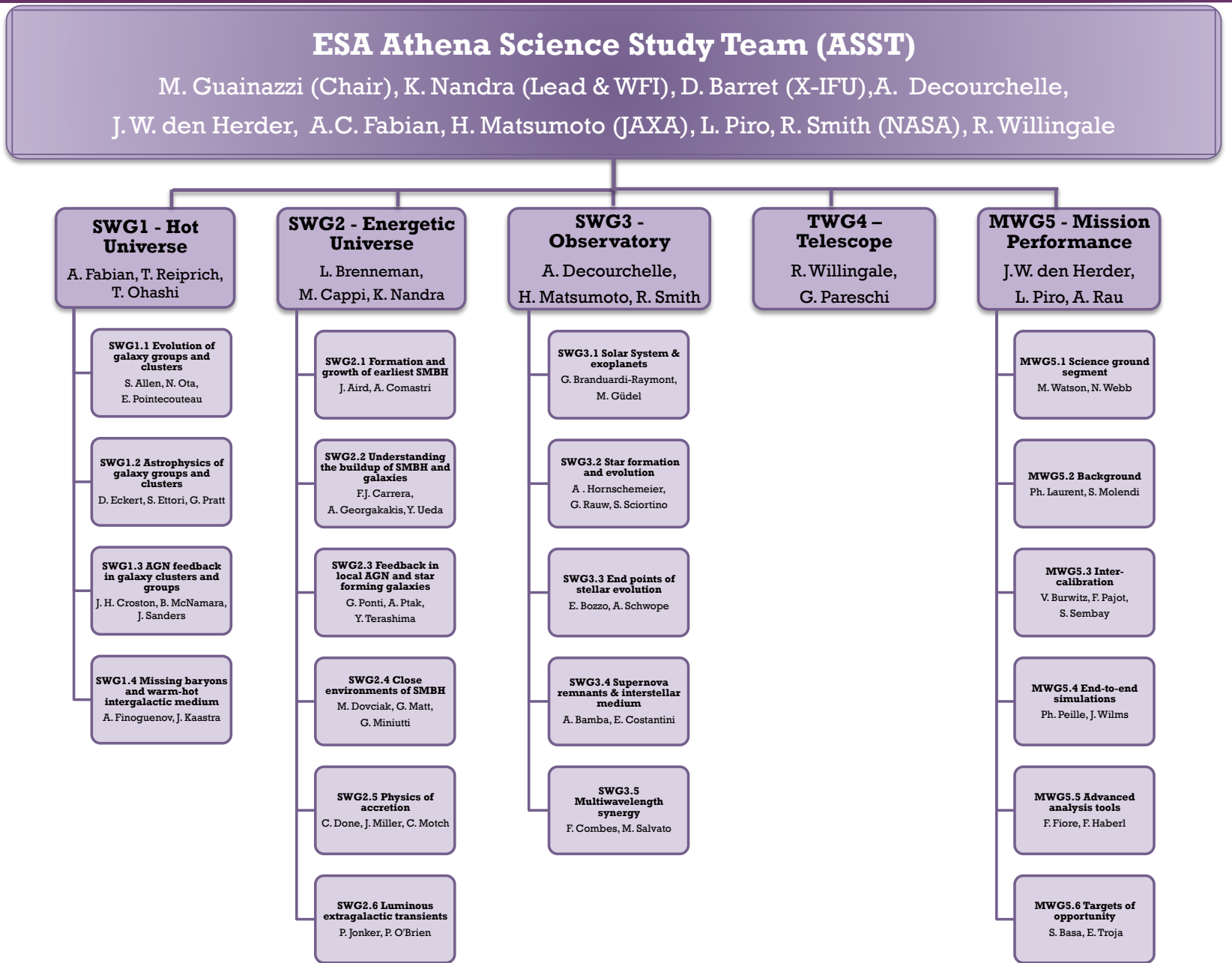
Athena Synergies with other facilities II

- *Athena*-Multi-messenger:
  - Led by: L. Piro (chair)
  - Started with workshop in Nov 2018 in Alicante (Spain)
  - LIGO/VIRGO, *LISA*, *Theseus*, KM3NET, ICECUBE, CTA
  - Compact object mergers, transients (TDE, GRBs), WHIM, SNRs, blazars…
  - WP expected by Q3 2019
- *Athena*-LSST
  - Team being assembled
  - WP expected within 2019

Athena Science Requirements

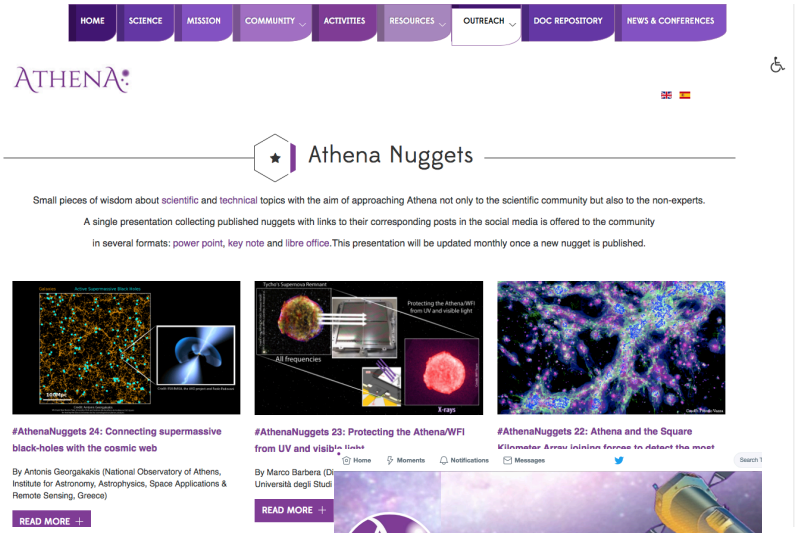
Parameter	value	enables (driving science goals)
Effective area at 1 keV	≥1.4 m^2	Early groups, cluster entropy and metal evolution, WHIM, high redshift AGN, census AGN, first generation of stars
Effective area at 6 keV	0.25 m^2	Cluster energetics (gas bulk motions and turbulence), AGN winds & outflows, SMBH & GBH spins
PSF HEW (≤ 7 keV)	5'' on axis, 10'' off axis	High z AGN, census of AGN, early groups, AGN feedback on cluster scales
X-IFU spectral resolution	2.5 eV 0.2-12 keV	WHIM, cluster hot gas energetics and AGN feedback on cluster scales, energetics of AGN outflows at z~1-4
X-IFU FoV	5' effective diameter	Metal production & dispersal, cluster energetics, WHIM
X-IFU background	< 5 10^{-3} counts/s/cm^2/keV 2-10keV	Cluster energetics & AGN feedback on cluster scales, metal production & dispersal
WFI spectral resolution	150 eV <80eV (1keV) & <170eV (7keV)	GBH spin, reverberation mapping
WFI FoV	40' x 40'	High-z AGN, census AGN, early groups, cluster entropy evolution, jet-induced cluster ripples
WFI count rate	1 Crab > 80%	GBH spin, reverberation mapping, accretion physics
WFI background	< 5 10^{-3} counts/s/cm^2/keV 2-7keV	Cluster entropy, cluster feedback, census AGN at z~1-4
Recons. astrometric error	1'' (3s)	High z AGNs
GRB trigger efficiency	50%	WHIM
ToO reaction time	≤ 4 hours	WHIM, first generation of stars

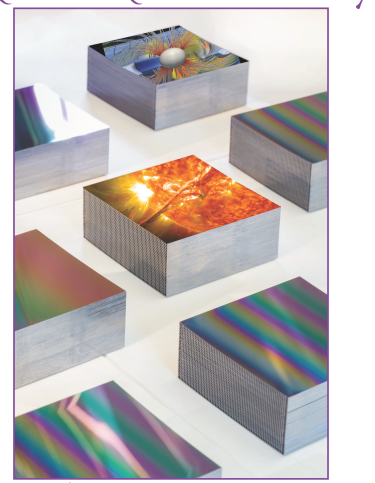
Athena Community Organisation



The Athena Community Office

- *Athena* is currently supported by about 800 researchers. Their scientific and technical expertise are key for the success of the mission.
- The ASST appointed the ***Athena* Community Office** to obtain assistance in:
  - Organisational aspects and optimisation of community efforts
  - Keep the *Athena* Community informed
  - Develop communication and outreach activities around *Athena*
- Led by IFCA (CSIC-UC) in Spain, with contributions from IRAP, MPE and UniGe





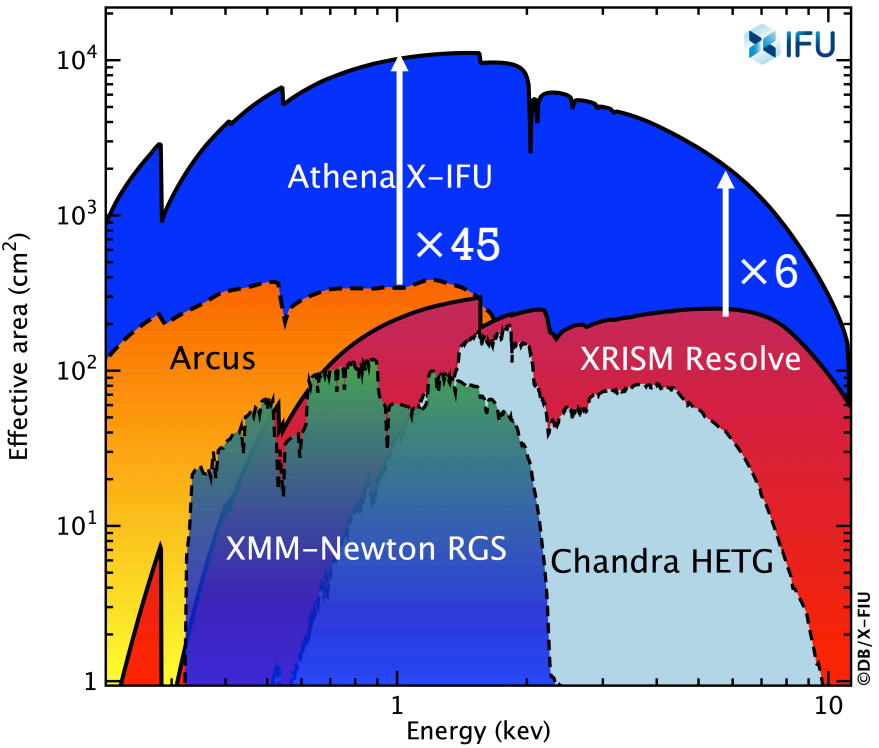
and Energetic Universe, n (China), January 2019

Athena Project development: Current status

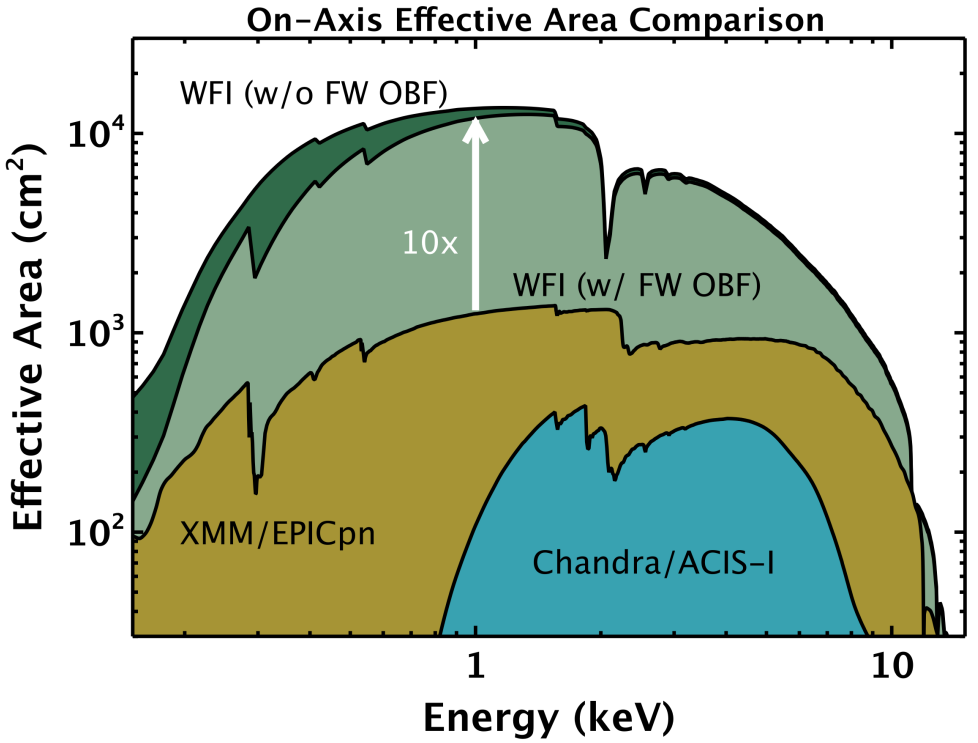
- Phase A ongoing, last milestone Status Review #1 (January 2018):
  - Comprehensively reviewed the Phase A work performed so far at the system level, including technical, cost and schedule aspects
  - Confirmed the good status of the spacecraft design and identified no showstopper to progressing towards adoption
- A modification of the mission baseline was needed to match mass- and cost-constraints:
  - A 15-row mirror baseline (limited science impact, preserving all major science requirements):
  - Reduction of the effective area at 1 keV from $2m^2$ to $1.4m^2$
  - Reduction of the nominal life from 5 years to 4 years
- Instrument consortia officially endorsed by ESA (Dec 2018)
- Instrument Preliminary Requirements Reviews (I-PRRs):
  - WFI finished Oct 2018
  - X-IFU expected for Feb 2019

Athena is a large effective area mission

X-IFU+mirror collecting area

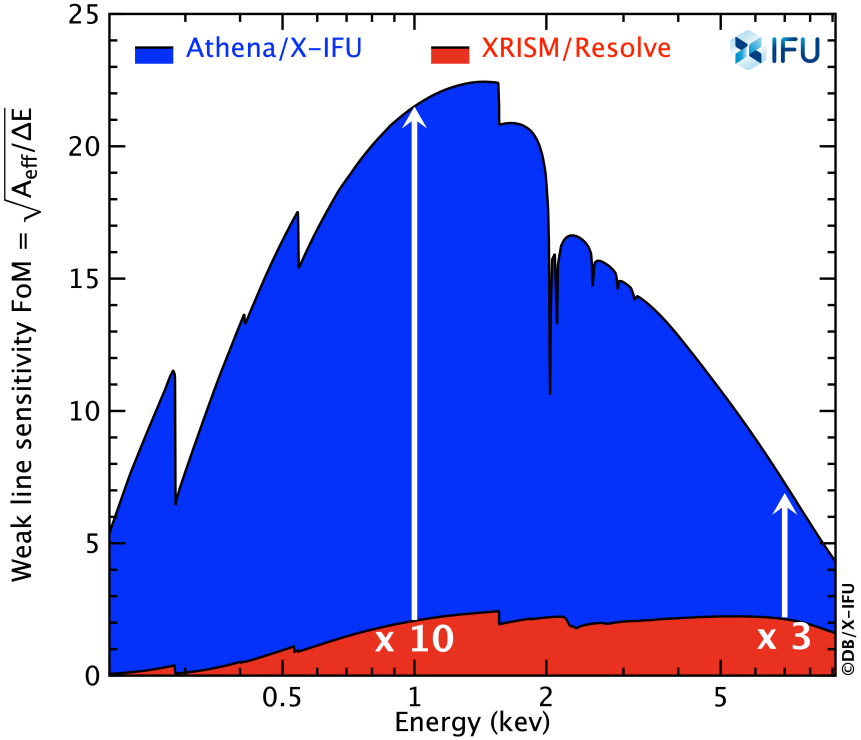


WFI+mirror collecting area

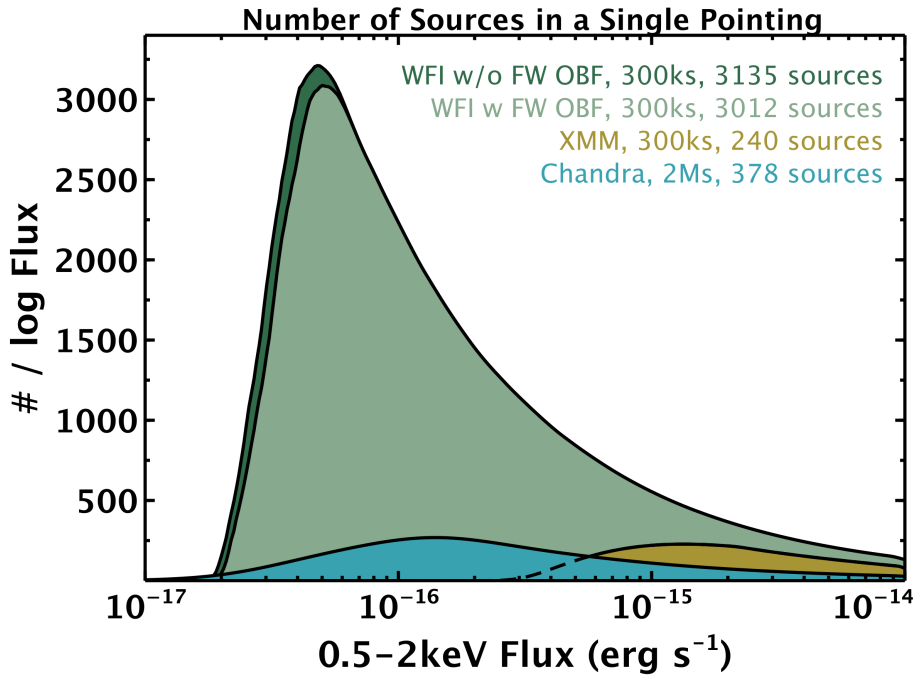


Courtesy A. Rau (MPE)

Athena: a transformational observatory



Weak line sensitivity comparison between X-IFU and XRISM



Flux distribution comparison between WFI and Chandra deep pointing

Credits: X-IFU team & J. Aird/A. Rau (WFI team)

Athena science objectives

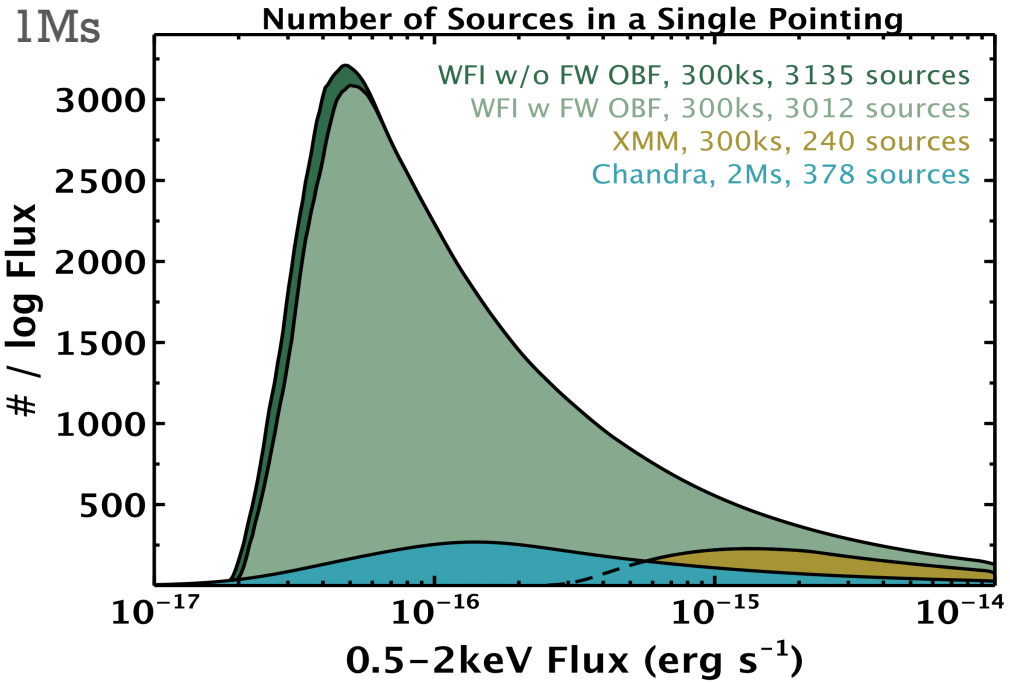
- Each broad science topic is translated into specific science objectives
  - Observing this-many objects of such-and-such type with such-and-such properties to understand their origin
  - e.g. R-SCIOBJ-221 Complete AGN census: Athena shall determine the accretion energy density in the Universe, by measuring the X-ray luminosity function and obscuration properties of the AGN population with at least 10 Compton thick AGN per luminosity bin (0.5dex) and redshift bins ($\Delta z = 1$) up to redshift $z \sim 3.5$
- Many of those concern observations of limited samples of objects of specific types
- But others require assembling those samples (rare objects, elusive objects…)
- To ensure these objectives are reached, the Athena team has assembled a Mock Observing Plan
  - Minimum set of observations that would yield those results within the lifetime of the mission (nominally 4y)
  - Also used to dimension engineering parameters (fuel…)

The Athena survey I

- Part of the Mock Observing Plan that provides samples of newly detected/characterized sources for some science objectives
  - Detection and characterisation of galaxy groups and clusters at z>2
  - Detection of AGN at z~6-8
  - Characterisation of Compton-thick AGN at z~1-3
  - Prevalence of Warm Absorbers and UFOs among the z~1-3 AGN population
  - ....
- From XMM-Newton/Chandra experience:
  - Some originated in Guaranteed Time and continued by the community
  - Many proposed and developed by the community
  - In coordination/synergy with other multi-wavelength facilities (EUCLID...)

The Athena survey II

- To be carried out with WFI
- Structured in several depths:
  - Wide "shallow" survey: ~100s × 10s ks (10s of deg^2)
  - Narrow deeper survey: ~10 × 100s ks (a few deg^2)
  - Pencil beam deep survey: ~4 × 1Ms



The Athena survey: definition

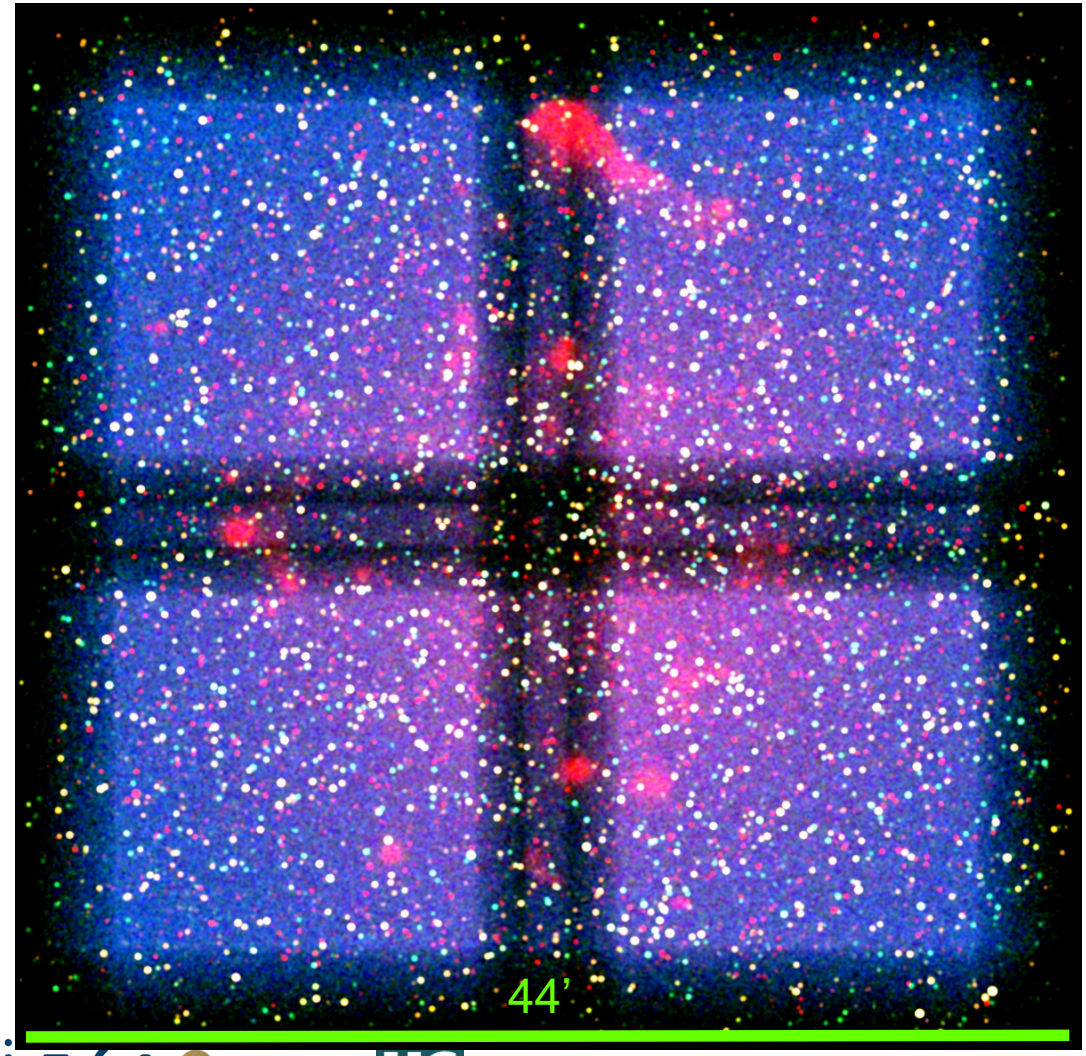
- Several incarnations as the science objectives evolved with the mission capabilities
  - Effort led by J. Aird with many contributors (A. Comastri, G. Lanzuisi, A. Georgakakis, Y. Ueda, S. Allen, N. Ota, E. Pointecouteau, L. Brenneman, M. Cappi, T. Reiprich, A. Rau, FJC…)

- How do we operate for source detection:
  - Simulate background: particle + Gal + "diffuse xgal" + sources from synthesis model
  - Drop/simulate our sources (galaxy clusters, AGN) on top of that
  - Detect sources

- How do we operate for source characterisation:
  - Simulate background spectrum: particle + Gal + "diffuse xgal"
  - Simulate source background
  - Model simulated background

Full SIXTE simulation of a deep field

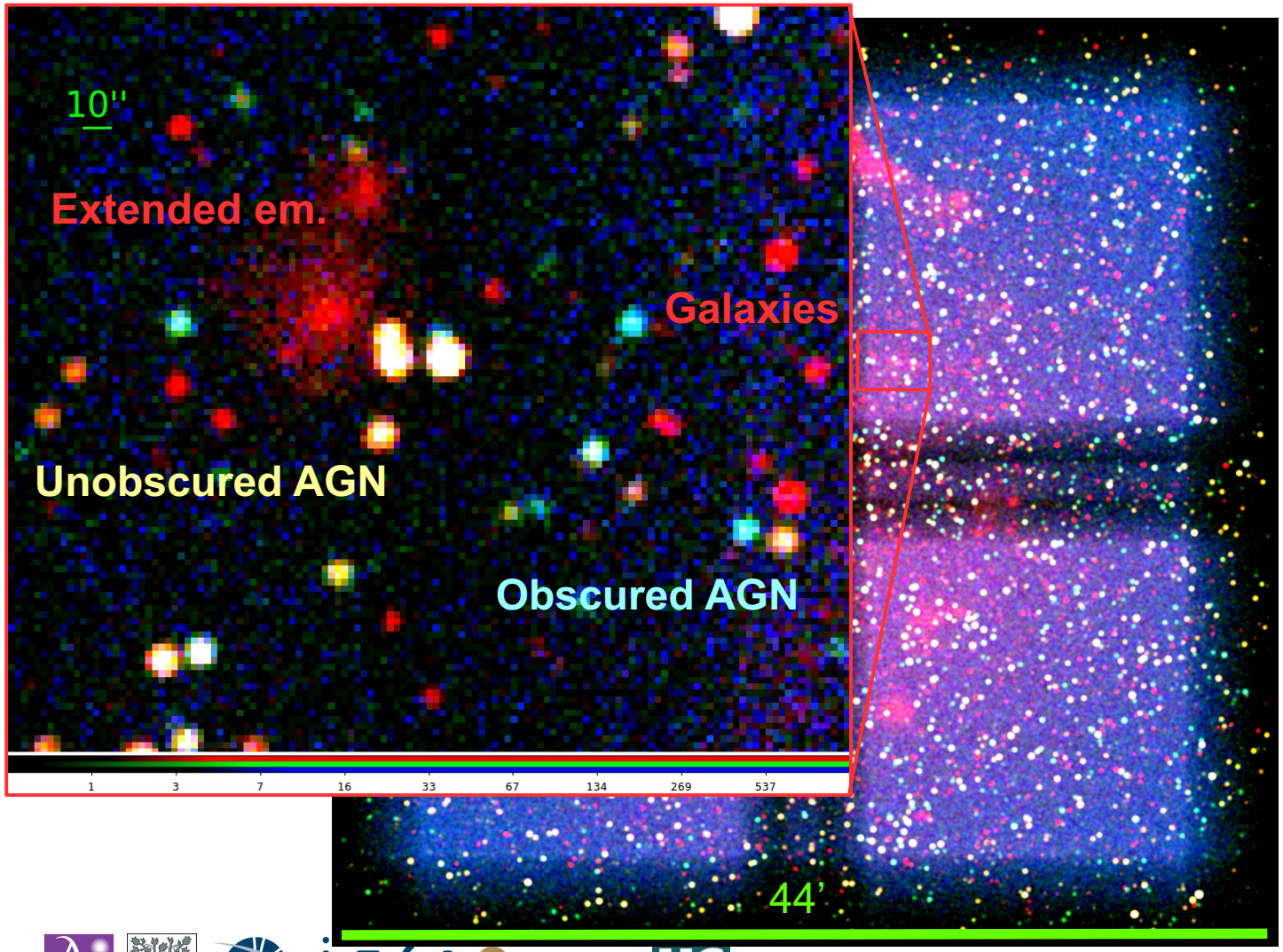
Result for 1Ms exposure (red 0.5-2, green 2-4.5 blue 4.5-10 keV)



Courtesy: G. Lanzuisi

Full SIXTE simulation of a deep field

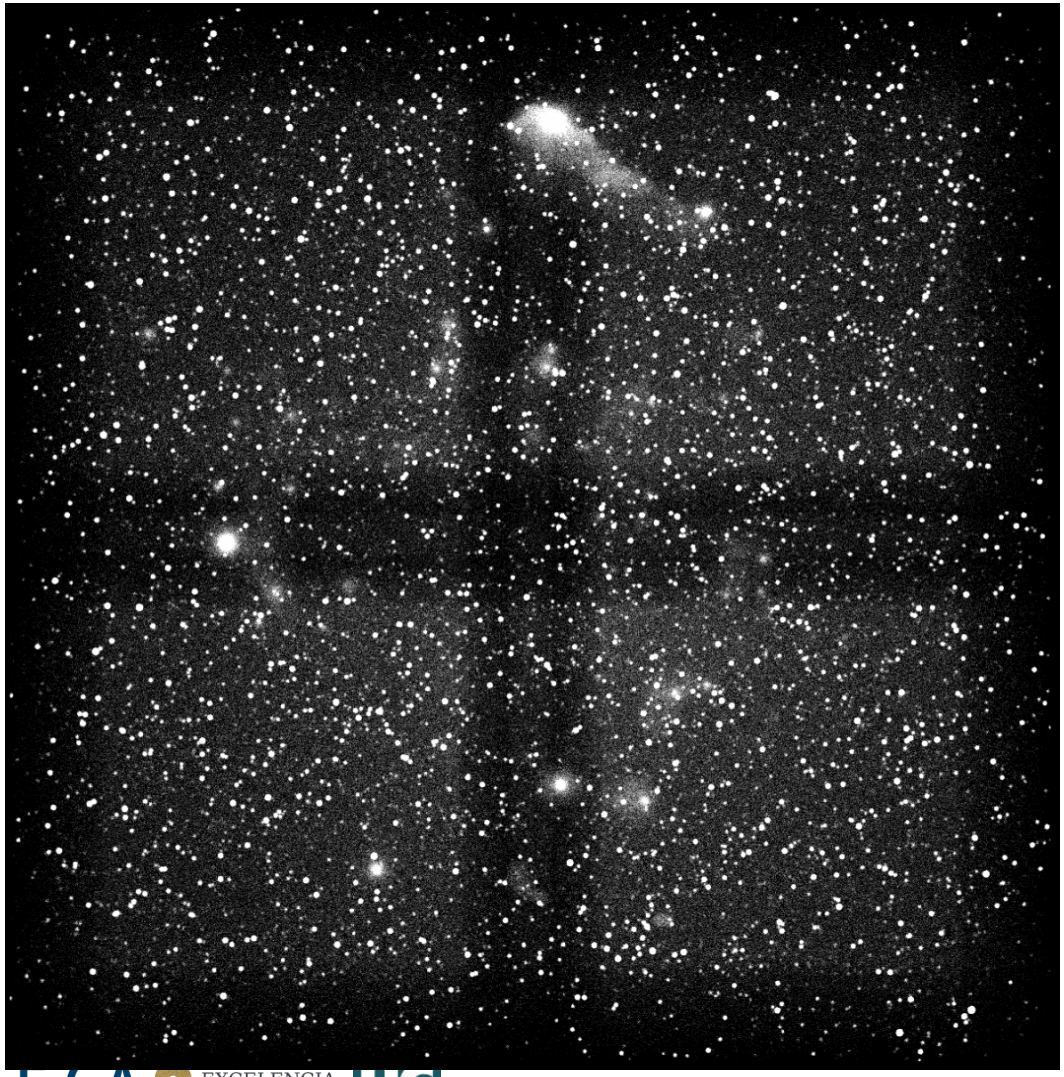
Result for 1Ms exposure (red 0.5-2, green 2-4.5 blue 4.5-10 keV)



Courtesy: G. Lanzuisi

Source Detection

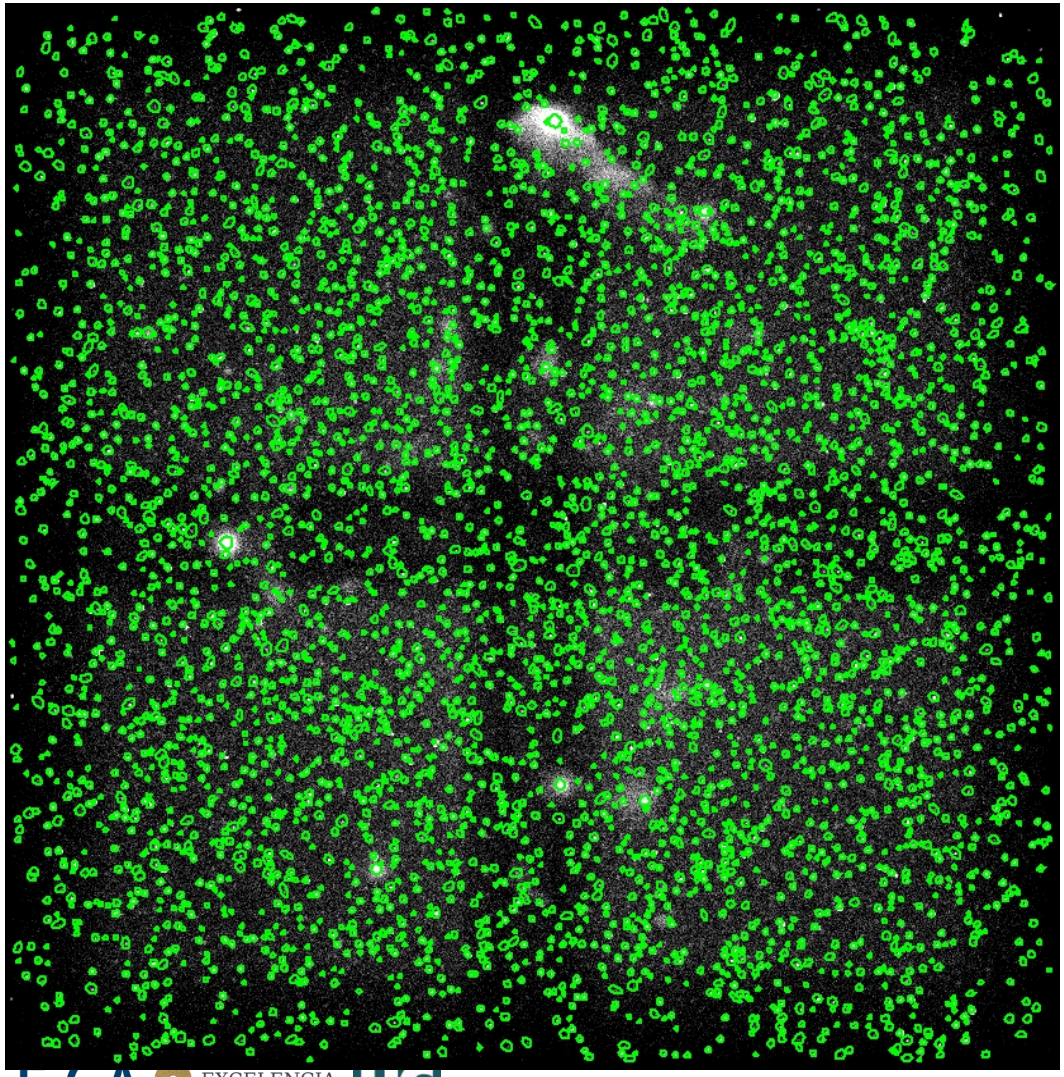
Run **wavdetect** on the 0.7-2 keV image



Courtesy: G. Lanzuisi

Source Detection

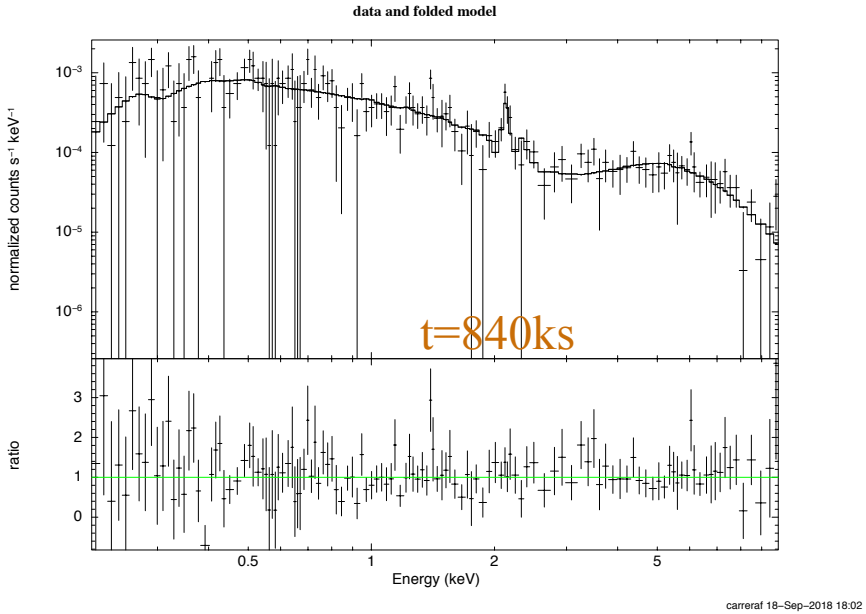
Run **wavdetect** on the 0.7-2 keV image

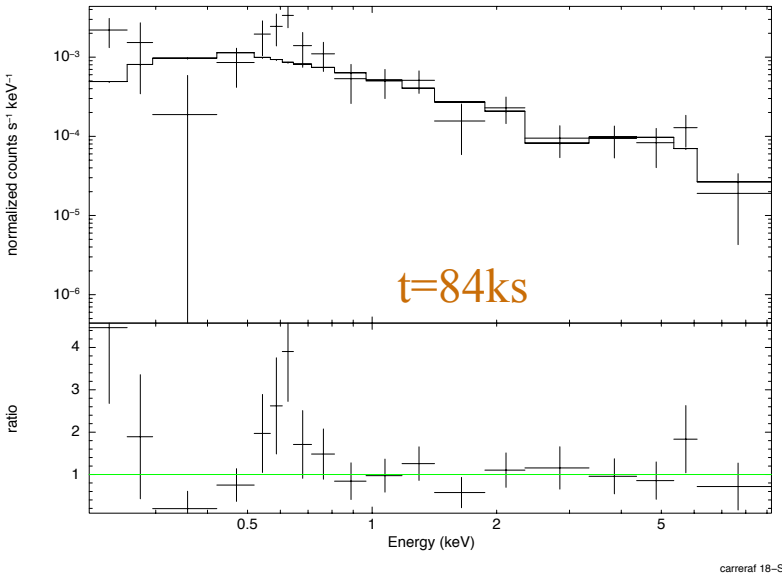


Courtesy: G. Lanzuisi

The Athena survey: definition

$\log N_H = 24.5$
$L_X(2\text{-}10\text{keV}) = 5 \times 10^{44}$ cgs
$z = 2$





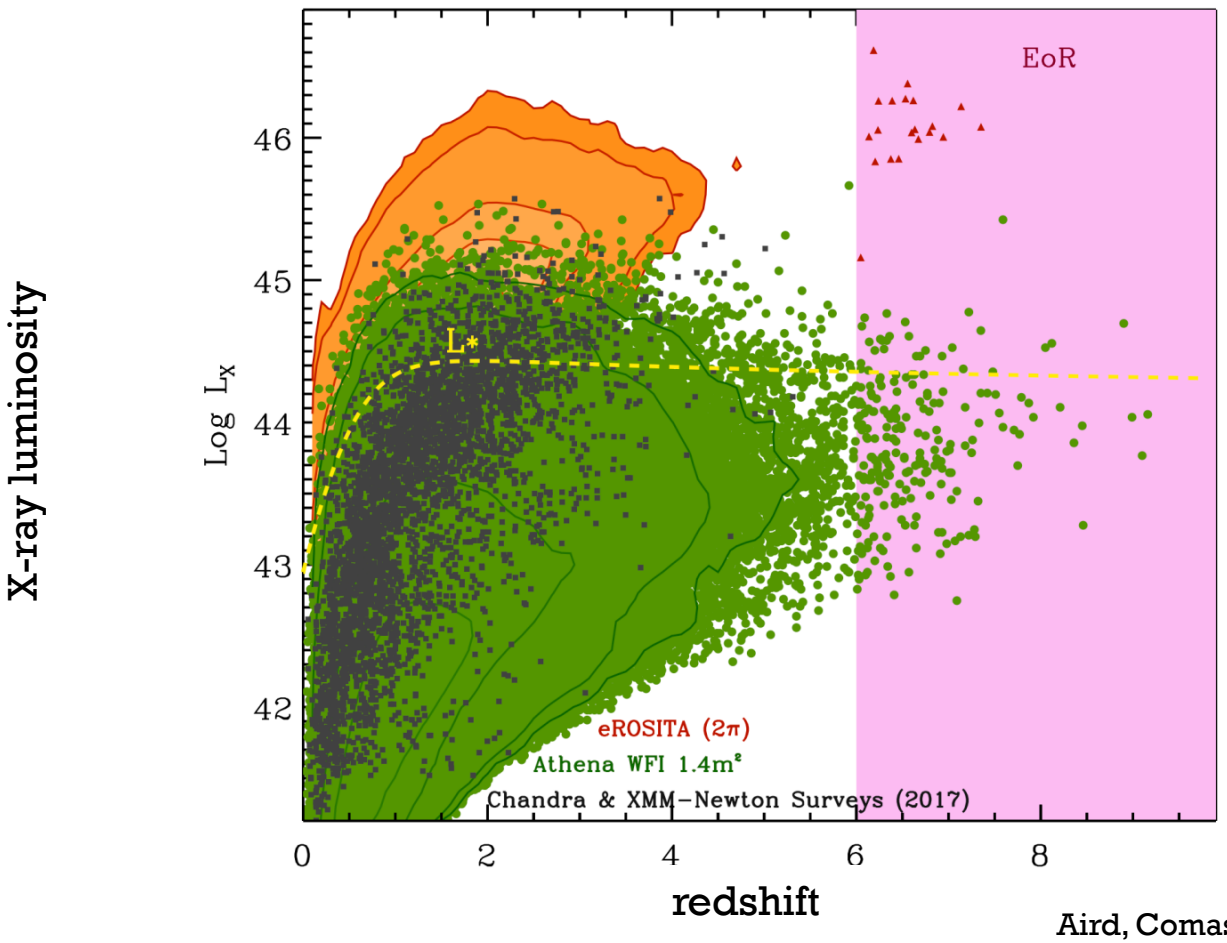
- How do we operate for source characterisation:
  - Simulate background spectrum: particle + Gal + "diffuse unresolved xgal"
  - Simulate source spectrum + background
  - Model simulated spectrum

The Athena survey: geometry

- As proposed: 4×1Ms+3×700ks+7×600ks + 289×80ks = 33.42 Ms
- As of May 2018: 14×840 ks+106×84 ks=20.66 Ms
  - Using 1.4m^2 mirror, 5´´ HEW PSF on axis, 2.3mm rib spacing, WFI with filter
  - Deeper depth driven by L*/10 AGN @z=6-7, L* CT AGN @z=1-3 (L,N_H)
  - Wider area driven by gal. groups @z>2 (T), ≤L* AGN @z=7-8, WA in L* AGN @z=3, UFO in ≤L* AGN @z=4

Detecting AGN in the Athena survey

AGN L_X versus z plane



Only most luminous /massive QSOs expected in opt/IR surveys

X-rays needed to signpost typical and obscured AGN

Aird, Comastri et al. 2013 arXiv1306.232
Updated by Andrea Merloni (MPE) (2017)

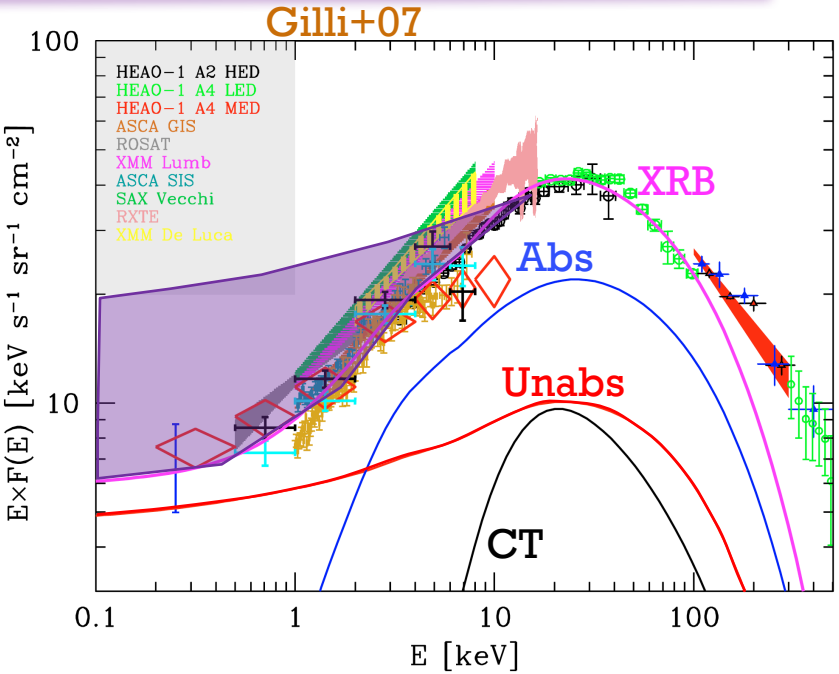
Outlook

- *Athena* will be a transformational X-ray observatory
  - Designed to address the Hot and Energetic Universe science theme
  - Will impact virtually every corner of astronomy
  - Will carry on deep and wide surveys of the extragalactic Universe
    - detect and characterise z>2 clusters of gals
    - detect z~6-8 $\lesssim$L* AGN
    - characterise z~1-3 ~L* CT AGN
    - characterise warm absorbers/UFO in $\lesssim$L* AGN z=3-4
    - ...
- It will be an essential part of the observational landscape in the early 2030s together with ALMA, ELT, SKA, CTA, LSST, etc.
- Vibrant community supporting it
- Key milestones: Phase A completion Mission Formulation Review end 2019, Mission Adoption end 2021 and Launch early 2030s

- Follow Athena on
  - Web: www.the-athena-x-ray-observatory.eu
  - Twitter: @athena2028
  - Facebook: The Athena X-ray Observatory
  - Athena Community Office email: aco@ifca.unican.es

Obscured AGN: why care?

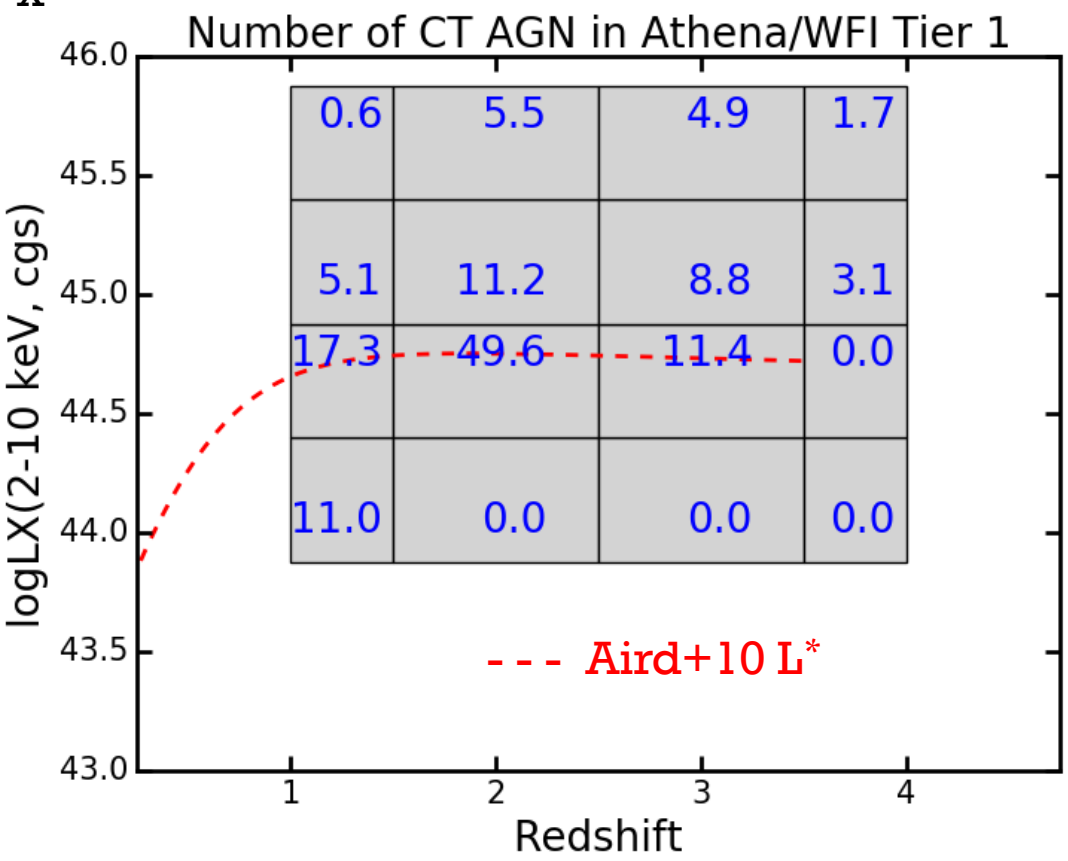
- Most energy emitted from accretion in the Universe is obscured
- Relationship between build-up of SMBH and growth of host galaxies:
  - through obscured phase z~1-4



- Unclear (but significant) contribution of Compton Thick (CT) objects
- One possible mechanism of direct influence of AGN on host galaxy: outflows (also radiation and jets, but another SWG)
  - Warm absorbers (WA)
  - Ultra-Fast Outflows (UFO)

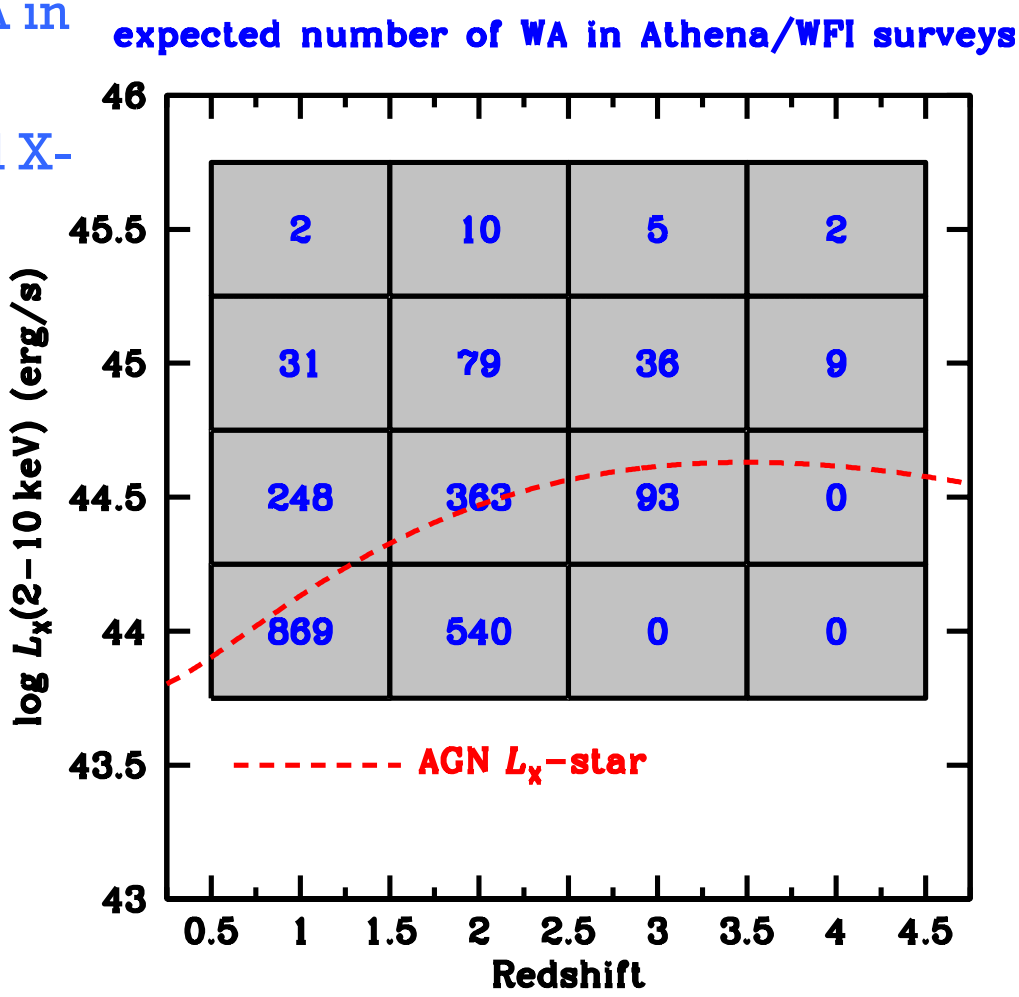
Heavily obscured (CT) AGN

- Complete census of heavily obscured (dominant?) AGN
- Recovering within 30% L_X and N_H (CT: $\log(N_H/cm^{-2})=24.5,25.5$) using only WFI spectrum and z
- Brightman&Nandra'11 torus
- Gilli+07 CXB model
- Including stray light
- Can do it for L* for $z \leq 3$
- Of course, in "real life" synergies with multi-λ data



Ionised absorption in AGN

- Aims:
  - Determine incidence of WA in general population of AGN
  - Provide targets for detailed X-IFU studies
- Recovering within 50% logξ(2-4) and $N_{H,ion}$ ($\log(N_{H,ion}/cm^{-2})$=22-24) using only WFI spectrum
- Ueda+03 XLF, 40% WA (Blustin+05)
- Using wide (60ks) tier of survey
- Can do it for L* for z≤3

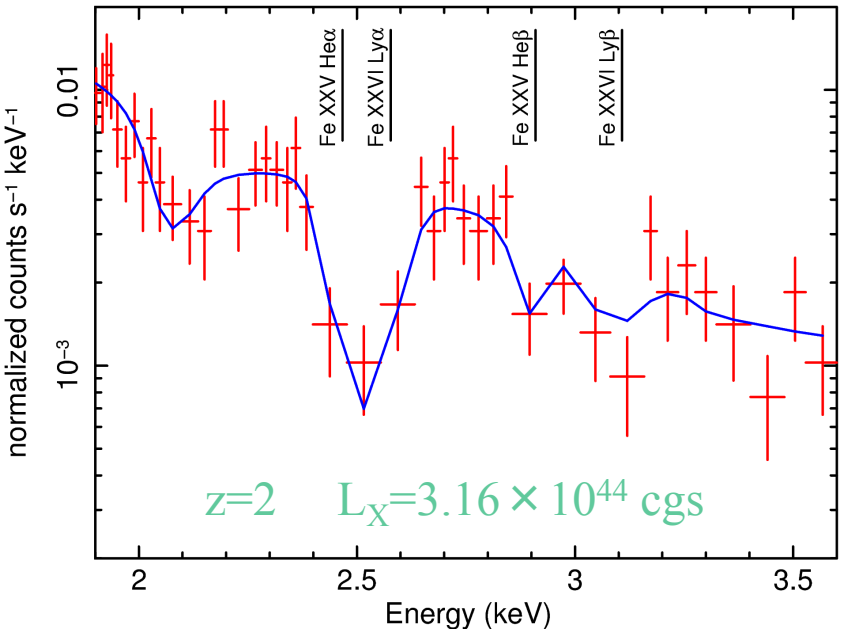


Credit: A. Georgakakis

Ultra-Fast Outflows in AGN

- Determine incidence, duty cycle and energetics of UFOs
- Detecting 6.7keV abs. feature at >5σ using only WFI spectrum
- $\log\xi=3.5$, $\log(N_{H,ion}/cm^{-2})=24$, $v_{turb}=3000$ km/s, $v_{out}=0.1c$ Lanzuisi+12
- Ueda+03 XLF, 30% UFO (Tombesi+10)
- Using wide (84ks) tier of survey: transient
- Can do it for $\log(L_X/erg/s)\geq44.5$ for $z\leq4$

Credit: G. Lanzuisi



Ultra-Fast Outflows in AGN

- Determine incidence, duty cycle
- Detecting 6.7keV abs. feature at >5σ using only WFI spectrum
- $\log\xi=3.5$, $\log(N_{H,ion}/cm^{-2})=24$, $v_{turb}=3000$ km/s, $v_{out}=0.1c$ Lanzuisi+12
- Ueda+03 XLF, 30% UFO (Tombesi+10)
- Using wide (84ks) tier of survey: transient
- Can do it for $\log(L_X/erg/s)\geq44.5$ for $z\leq4$

Credit: G. Lanzuisi